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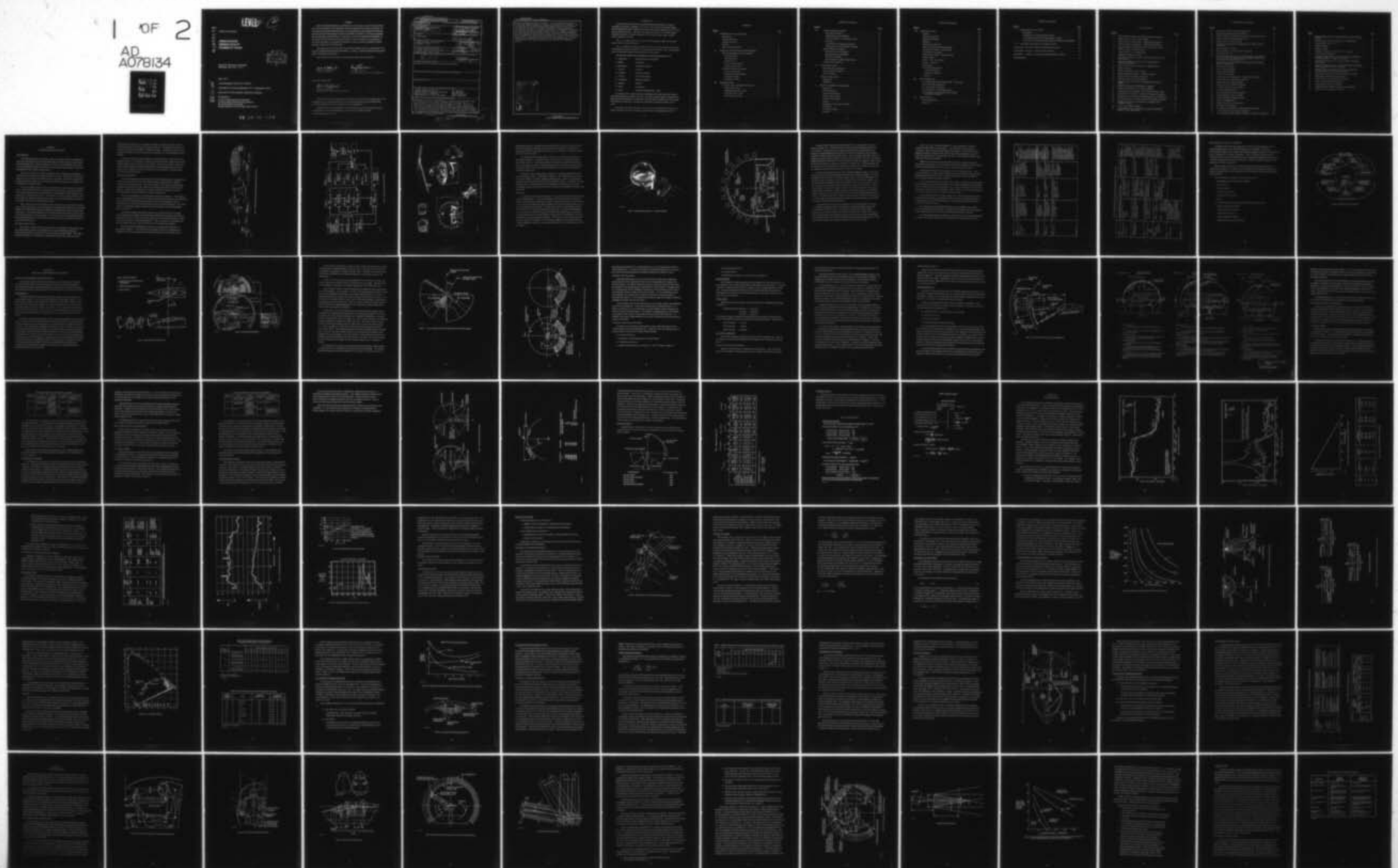

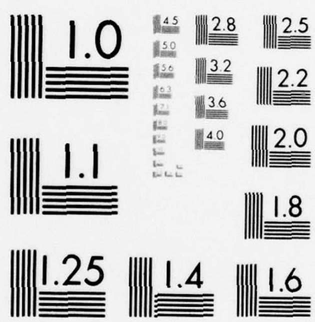
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CREW STATION DESIGN FACILITY FEASIBILITY STUDY

Grumman Aerospace Corporation
Bethpage, New York 11714

May 1979

Technical Report AFFDL-TR-79-3037

Final Report for Period September 1977 — December 1978

Approved for Public Release; Distribution Unlimited

Prepared for:
Air Force Flight Dynamics Laboratory
Air Force Wright Aeronautical Laoratories
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

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This technical report has been reviewed and is approved for publication.

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TRANSLUCENT/OPAQUE LIGHTING ENCLOSURES	MOTION SIMULATION

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report addresses the feasibility of a new and unique facility capable of simulating the total range of lighting conditions experienced in military aircraft crew stations during operational flight. The facility would provide a means for evaluating the impact of extreme illumination levels on the legibility of displays and instrument/panel lighting systems to be incorporated in advanced crew stations. This facility would interface with the flight simulation test facilities already established at the Flight

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Control Development Laboratory at WPAFB. At the beginning of this effort, two baseline lighting simulation systems were selected for development. One configuration uses an opaque dome shaped lighting enclosure with internal sky illumination sources. The other configuration uses a translucent enclosure with external sky illumination sources. Techniques for simulating sky intensity and color, sun/moon intensity and color, reduced visibility, air-to-air and air-to-ground visual effects, terrain, and motion simulation were investigated for each baseline configuration. The principal conclusion of this study is that real levels of sky and sun luminance, colors and color shading can be simulated and controlled (with some limitations) utilizing the translucent dome lighting enclosure with external sky illumination sources.

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FOREWORD

This final report describes the engineering effort performed by Grumman Aerospace Corporation, Bethpage, New York, 11714, for the Crew Station Design Facility Feasibility Study in support of Project 6190 (Control Displays for AF Aircraft and Aerospace Vehicles). This work was sponsored by the U.S. Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, under contract number F33615-77-C-3067.

Mr. J. A. Uphaus was the Air Force Project Engineer during the conceptual phase of the work reported herein.

Mr. J. Connelly was Project Manager for the Grumman Aerospace Corporation. This position was formerly held by Mr. T. Hine who has retired. Mr. S. LaCarrubba was the responsible Engineer and coordinator of this report.

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T. Hegerty	-	Software
A. Kelvin	-	Life Science
T. Twist	-	Consultant (Hoffman Eng. Corp.)

The authors wish to thank the many individuals in the commercial and military aircraft manufacturing industry, the lamp, solar and projection system manufacturers, plastic dome manufacturers, in addition to the University of California for their excellent voluntary cooperation in sharing their experiences during the conduct of this work.

This report was first submitted to the Air Force in February 1979 and the time period covered by this report was from September 1977 through December 1978.

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SECTION I
INTRODUCTION AND SUMMARY

BACKGROUND

At the beginning of the last decade, cockpit simulators had been developed to a point where the aircraft dynamics and flight control system response to pilot inputs could be duplicated in a realistic fashion. At that time, little had been done in the way of developing realistic out-the-window visual displays and attempts to overcome that deficiency were rapidly being pursued.

These new attempts to increase the fidelity of the simulators by introducing external visual cues met with varying degrees of success. Most of the developments taking place were directed at trying to achieve a favorable trade-off or compromise in those parameters which were considered essential to achieving a reasonable level of fidelity of the external scene.

The visual displays developed were represented by a diverse range of configurations: closed circuit television, both black and white and color, using model boards or computer generated inputs; projected films; and point light source reflective and transparency projections and others. None of these, however, addressed the problem of operation in a highly illuminated environment, but were all designed to operate in low ambient light levels, usually darkened areas.

Today, with the increasing workload on the pilot and crew to perform necessary tasks, factors which before were considered of secondary importance become primary effectors in determining the maximum effective workload that the pilot and crew can accomplish. The ambient lighting and cockpit illumination now become a major factor in determining optimum cockpit design. It is desired then to have available a facility which will simulate these external illumination levels for man-machine evaluations in a controlled environment.

PROGRAM OBJECTIVES

The objective of this effort was to determine the feasibility of fabricating a new and unique facility capable of simulating the total range of lighting conditions experienced in military aircraft crew stations during operational flight. This effort included investigation of methods for simulating the entire range of sky and solar luminance levels and colors, atmospheric conditions affecting visibility, aircraft/ visual scene motion and moving air and ground targets. The lighting simulator would utilize a fixed base, single place or multicrew cockpit. The simulator would also be computer controlled, thus permitting precise simulation of realistic lighting mission profiles.

The factors with the greatest influence on the performance of the study and its findings are the use of a fixed base cockpit (a Statement of Work requirement) and the high illumination levels that have to be produced. Briefly summarized, a fixed base cockpit concept requires rapidly changing the lamp intensity and color for sky and terrain scene simulation to provide an accurate visual rendition of simulated pitch, roll, and yaw aircraft motion.

PROGRAM APPROACH

Prior to investigation and development of baseline lighting system configurations suitable for incorporation in the Crew Station Design Facility (CDSF), a lighting mission profile was formulated. This profile (Figure 1) illustrates the dynamically changing visual environment that might be encountered by the pilot during a typical mission. During this investigation, the mission profile was utilized as a guide to development and evaluation of baseline simulator capabilities.

This study was guided by the general plan illustrated in Figure 2. This illustration is self explanatory except for a few places where interactive tasks are not indicated. In the selection of candidate baseline systems (Task 1), the questions of motion simulation (Task 7) and sun movement (Task 4) were major considerations. The power (Task 11) consumption analysis results were used as inputs in the heat dissipation analysis (Task 5).

Two baseline lighting simulation systems were selected in Task 1 for study. Each baseline system design was developed and evaluated in accordance with Tasks 2 through 8 (Figure 2) in order to provide a valid basis for selecting the baseline system which offers maximum simulation capabilities. After completing an investigation of the two baseline systems, a third baseline system was briefly investigated.

The first baseline configuration, referred to as External Sky Simulation is illustrated in Figure 3. The spherical dome lighting enclosure is translucent; sky luminance and color are generated by external luminaries that surround the dome.

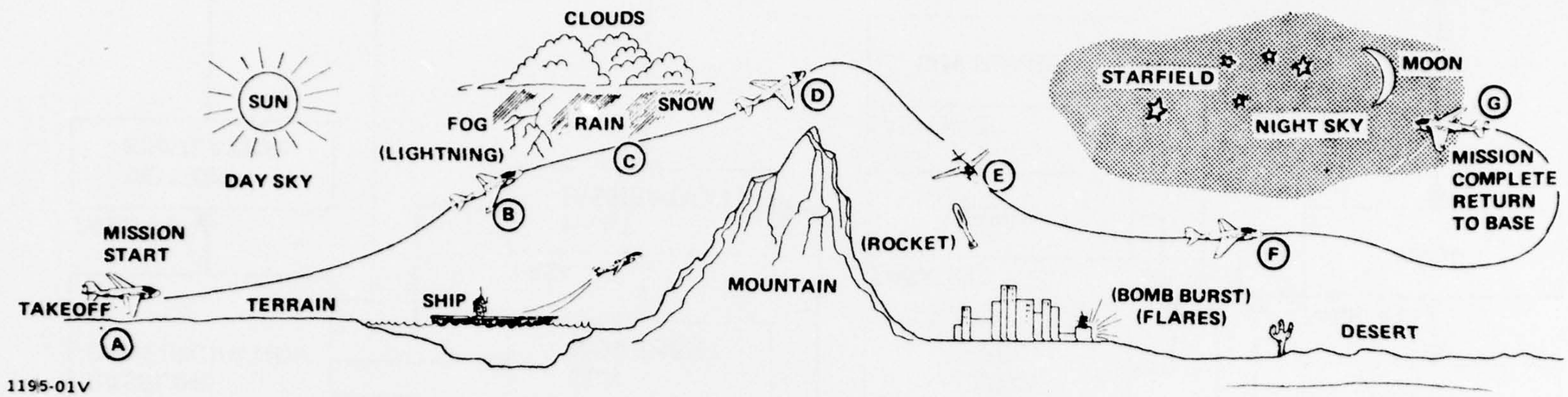

Figure 1. CSDF Mission Profile with Programmed Environmental Luminance

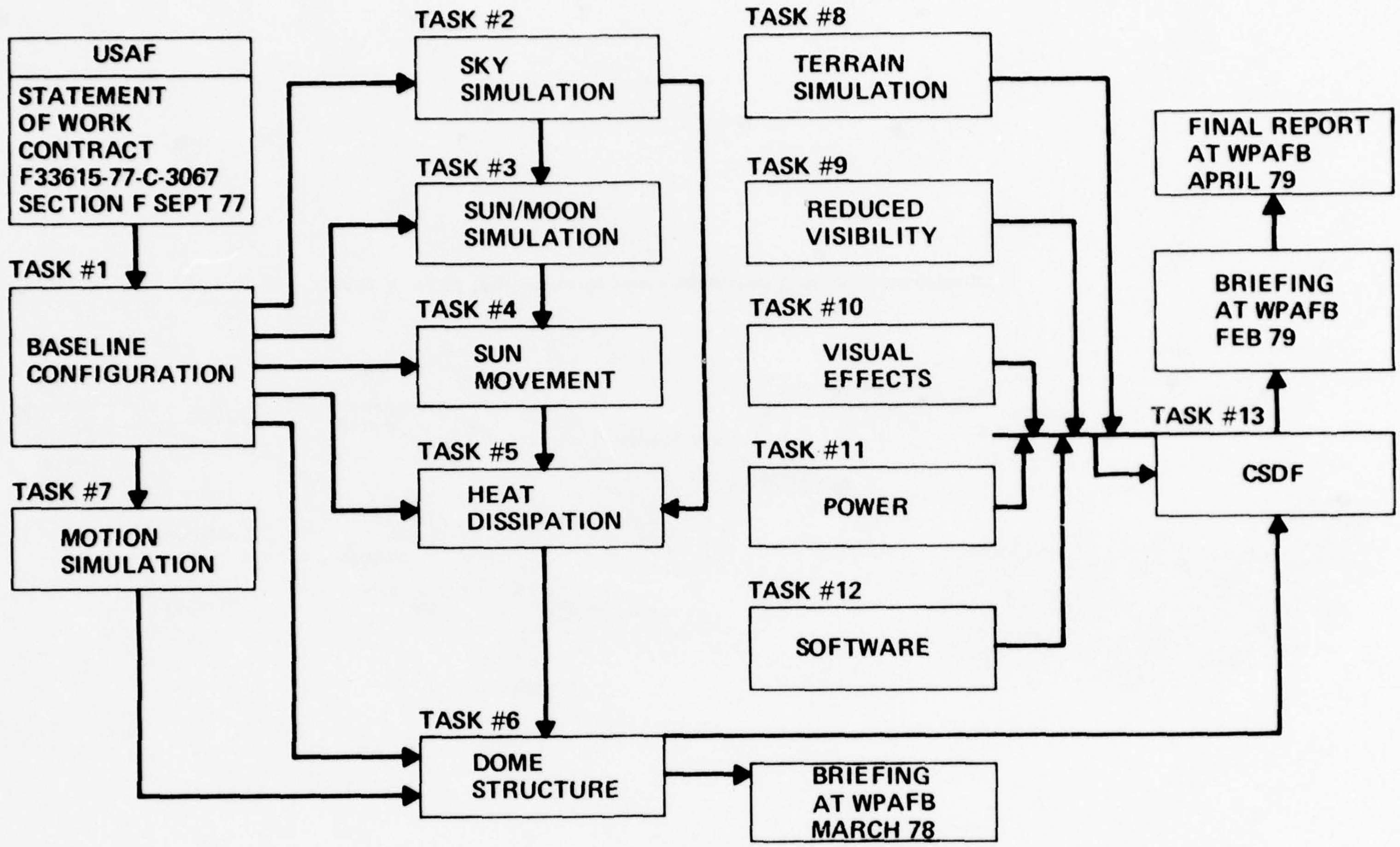

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Figure 2. Study Plan Crew Station Design Facility

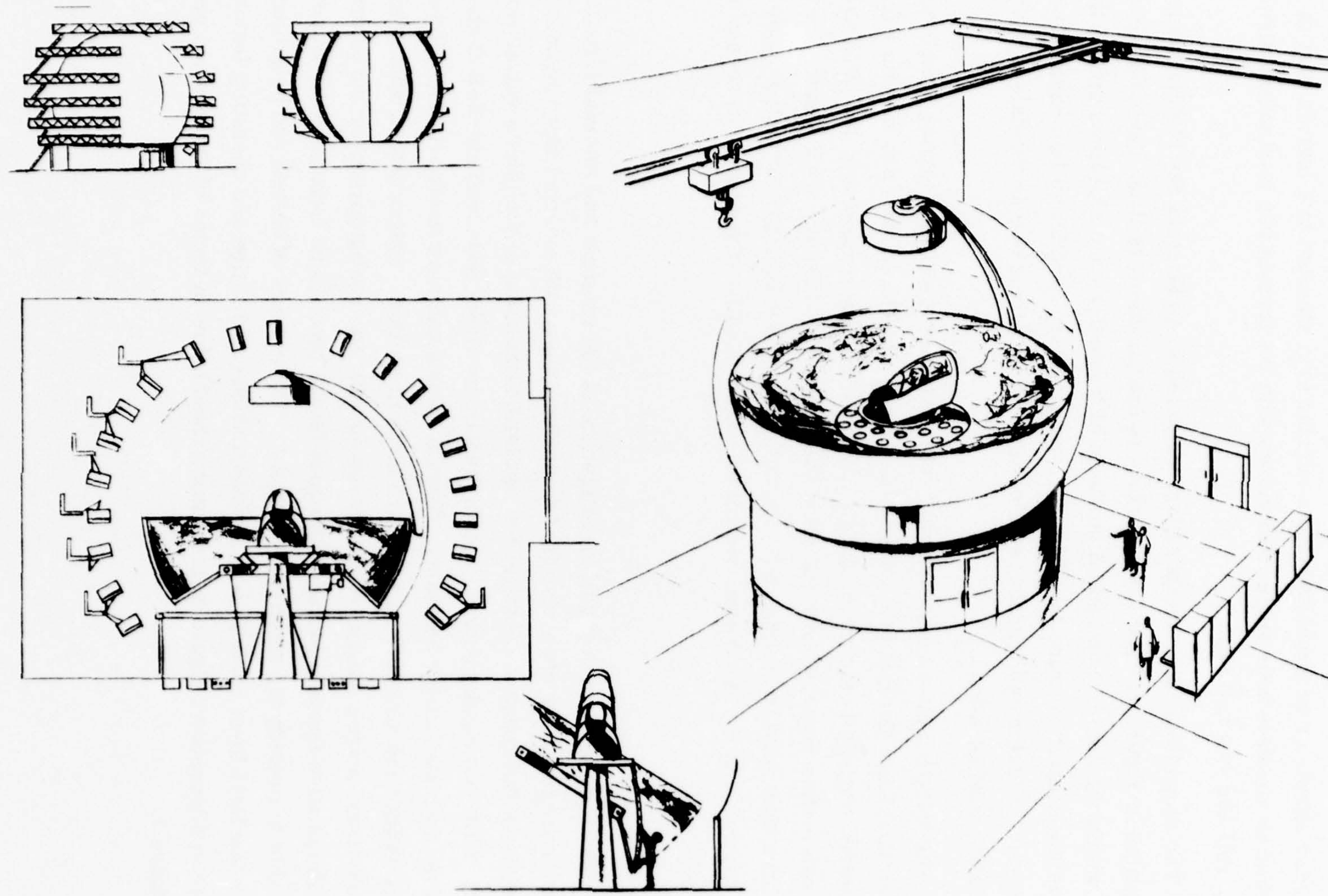

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Figure 3. CSDFS Baseline Configuration – External Sky Simulation

Internal luminaires are utilized to project cloud effects on the dome's inner surface. The solar simulator is gimballed (via a carrier arm attached to a terrain pan) in elevation to simulate hour angle, and moves with the terrain pan to simulate aircraft pitch, roll and yaw motion.

The second baseline configuration, referred to as Internal Sky Simulation is illustrated in Figure 4. The dome surface is opaque and it is illuminated entirely from within the dome. Substantial numbers of luminaires are clustered around the base of the cockpit in order to achieve the required sky simulation luminance levels. The solar simulator and terrain pan mechanization is the same as the external sky simulation configuration.

The third baseline configuration, referred to as External Lighting Simulation with Moving Base Cockpit is illustrated in Figure 5. The terrain pan may be raised or lowered slightly to simulate changing aircraft altitude. However, the pitch and bank pan motion required with the fixed base cockpit is absent. As a result, the dome wall area that must be illuminated at sky luminance levels and color is the upper hemisphere; with the fixed base cockpit this area must be 65% greater to accommodate pan motion.

RESULTS

The results of an in-depth investigation of the external and internal illumination system configurations show that the translucent dome with external sky simulation sources has the greatest potential for realistic simulation of the pilot's visual environment. With this configuration, high luminance level sky and cloud simulation can be achieved with good color contrast. Terrain scenes can have appropriate luminance levels without the simulation of forward aircraft motion. Projection of landing and takeoff visual scenes cannot be accomplished with this configuration (or the Internal Sky Illumination System) at high luminance levels because no technology is presently available to provide the necessary contrast. These types of scenes can be projected under low light level conditions. The simulation capabilities and operating features of this configuration (Figure 3) are summarized below in terms of the mission profile in Figure 1.

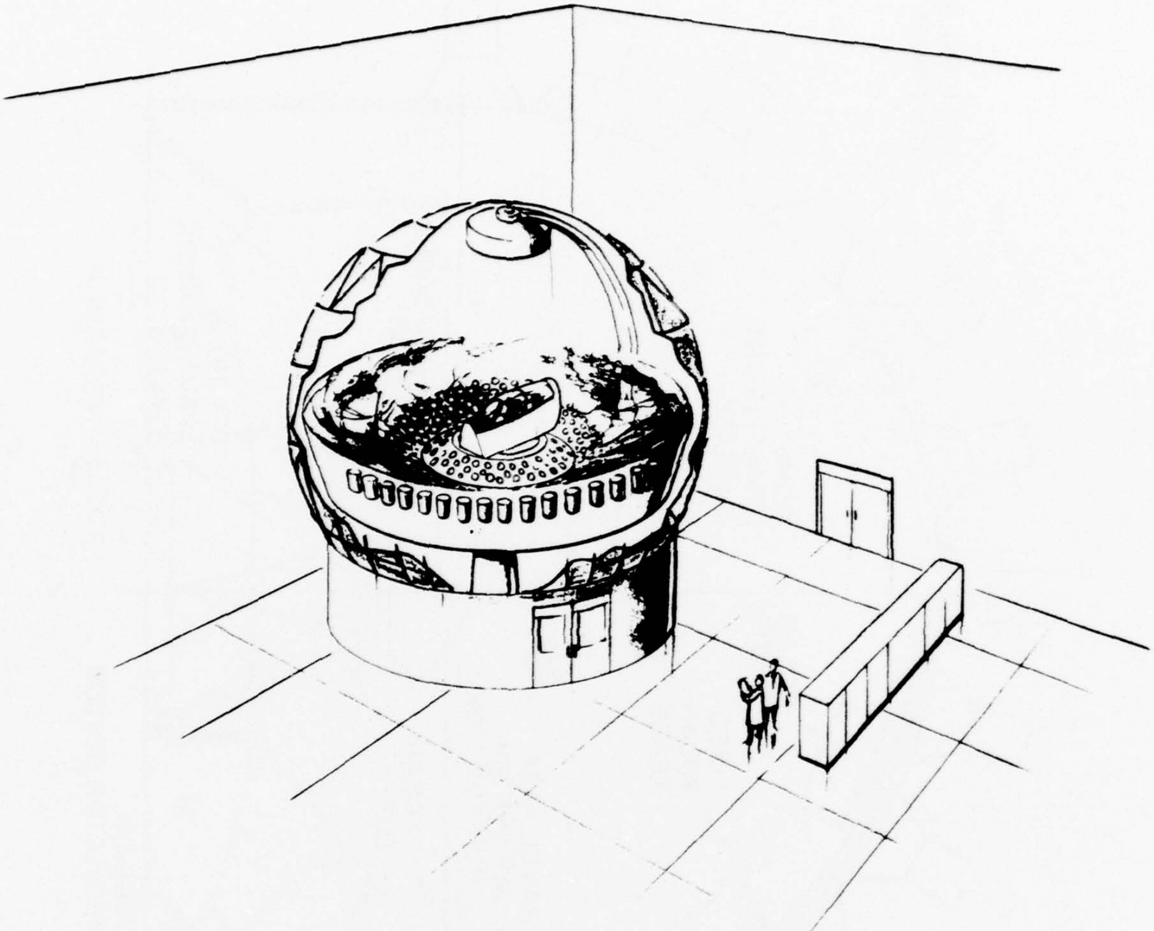

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Figure 4. CSDFS Baseline Configuration — Internal Sky Simulator

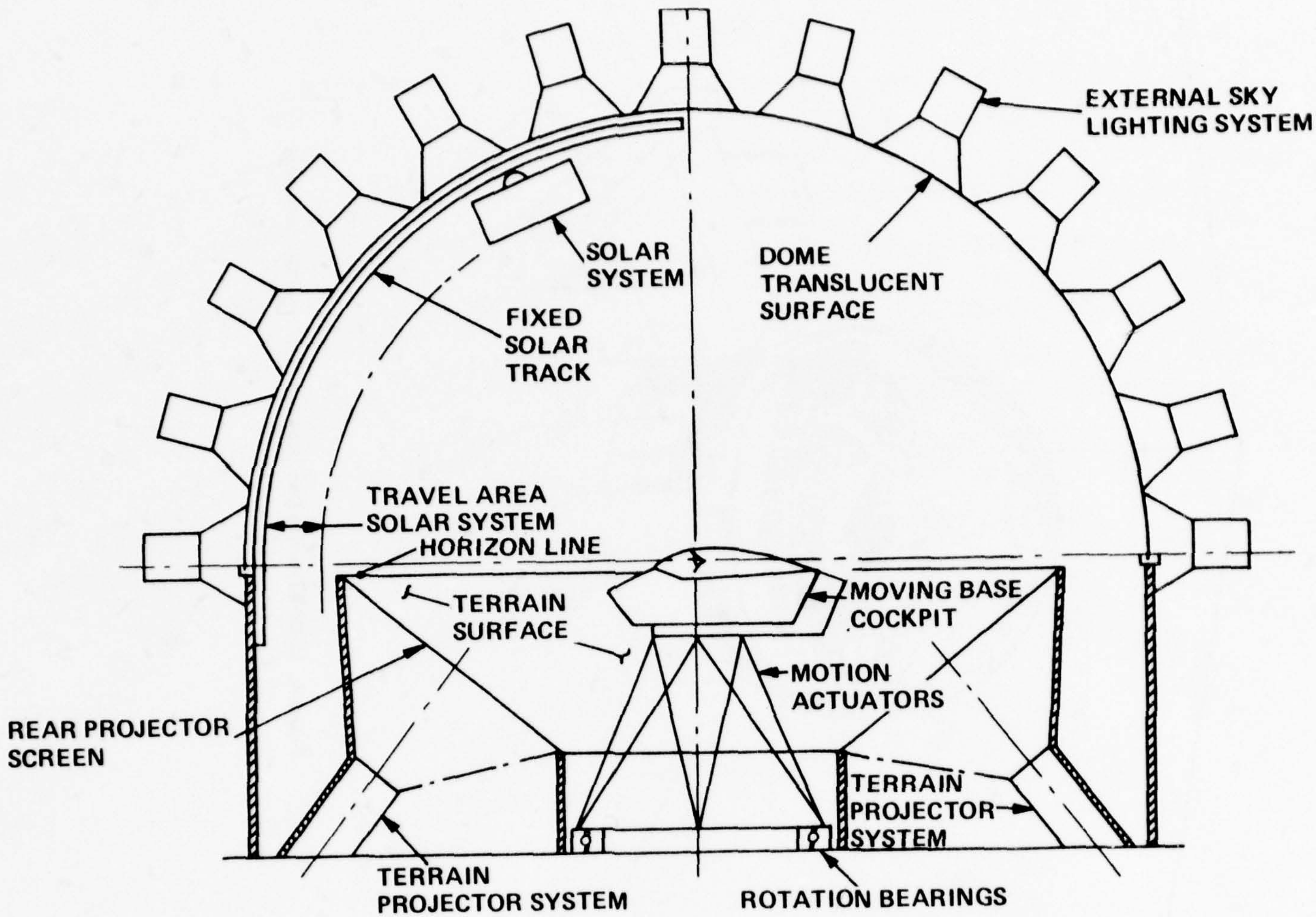

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Figure 5. External Lighting Configuration With Moving Base Cockpit

A typical mission might start during daylight hours on an airfield runway on a clear day (Figure 1-A). The aircraft takes off in an easterly direction with the sun over the nose. During the climb, aircraft pitch and roll motion simulation will be achieved by programming the terrain pan to move about the fixed base crew station in response to control inputs and aircraft motion. Thus, the horizon line tilts to simulate changes in aircraft attitude relative to the earth and sun position. Due to the terrain pan design configuration, pitch and roll motion would be limited to $\pm$ 30 degrees. Pitch and yaw velocities are limited to 1 radian/sec and roll to 4 radians/sec. Altitude changes will be simulated by either raising or lowering the pedestal that the cockpit is mounted on or by raising or lowering the terrain pan with respect to the cockpit.

As the aircraft banks and turns, direct sunlight suddenly impinges on consoles, indicators and controls producing high luminance levels within the cockpit. The solar simulators will be capable of illuminating either tandem or side-by-side fighter cockpits with 10,000 foot-candles. The sun's collimated rays, color from sunrise to sunset and resultant illuminance incident upon displays in the test cockpit will be consistent with the levels reached had that cockpit been exposed to the real world. Time of day simulation is achieved by angular rotation of the solar carrier arm with respect to the horizon (terrain pan). During daylight, terrain illuminance, color and texture can be simulated, but there will be no high resolution detail defining specific ground objects. Sky intensity and color rendition can be accurately simulated by programmed computer control of the filtered luminance output of external luminaires surrounding the upper portion of the translucent dome.

Approaching cloud cover above and ahead of the aircraft (Figure 1-B) can be simulated by programmed control of luminaires mounted beneath the cockpit and outside the pilot's field-of-view. Simulated clouds below the aircraft will be generated by a remotely located fog machine (see Figure 42). Clouds at the horizon will be projected above the periphery of the horizon pan; these will be synchronized with aircraft motion. Jets located around the cockpit (outside the field-of-view of the pilot) will be used during simulated penetration of cloud cover and fog.

"Snow" and "rain" simulation (Figure 1-C) can be achieved by ejection of transparent pellets near the crew station. To avoid damage to the simulation mechanism, water would not be used within the simulator. It should be noted that significant problems associated with control of fog, rain and snow may occur if a forced air cooling system is needed within the dome. These problems will not occur during night simulated operations.

Flight above cloud level where cloud albedo produces a marked increase in illuminance level (Figure 1-D) is simulated by programmed changes in sky color above the aircraft and appropriate injection of fog to simulate cloud cover below.

Programmed reduction in sky luminance occurs as dusk approaches. Moon simulation (Figure 1-E) can be achieved using the solar simulator in conjunction with the appropriate dousers and masks. Relative motion of the moon in the night sky will be synchronized with aircraft maneuvers.

As the aircraft approaches the target area, rockets, bomb bursts, and incendiary flashes and flares are encountered under the dark sky field producing sudden luminance and color changes within the cockpit (Figure 1-F). Flash and flare due to ground and air delivered weaponry can be simulated by strobes, video or motion picture projection. Low ambient light makes these simulation methods feasible.

As the aircraft returns to its base (Figure 1-G), visual scene and motion simulation can be achieved with a high degree of fidelity under low ambient illumination. At night landing, ground roll and braking can be realistically simulated by means of a television projection system.

The typical mission profile described above can be modified in any manner within the capabilities of the simulator. Lighting mission profiles can be programmed and controlled through the use of the crew station design facility computers.

The engineering simulation components, design limitations and interface problems pertinent to the external lighting system configuration are summarized in Table 1.

Table 1 External Illuminated Crew Station Design Facility Simulation Concept (Sheet 1 of 2)

TASK	A SIMULATED DESIGN APPROACH	B DESIGN LIMITATIONS	C SYSTEM INTERFACE PROBLEMS	D REMARKS
NO. 2 SKY SIMULATION DAY/NIGHT	• EXT. BASELINE CONCEPT METAL HALIDE LAMPS – 1200 w SPECIAL DESIGNED LUMINAIR WITH MULTI-FILTERS & ASSOCIATED SUBSYSTEMS	• INTENSITY AND COLOR RESOLUTION LIMITED BY THE NUMBER OF LAMPS THAT CAN BE USED	• THERMAL CONTROLS • ENVIRONMENT CONTROL – UV & OZONE • SYNCHRONIZATION OF SYSTEM ILLUMINATION WITH MOTION	• SKY SIMULATION INTENSITY AND COLOR RESOLUTION DAY/NIGHT CAN BE ACCOMPLISHED • SOME R&D TESTING REQUIRED BEFORE LIGHTING SIMULATION EQUIPMENT AND ENVIRONMENTAL CONTROL DESIGN REQUIREMENTS CAN BE ESTABLISHED
NO. 3 SUN/MOON SIMULATION	• INTERNAL DIRECT CARRIER ARM POSITION • LAMPS XENON 30 KW (1 REQ'D PER CREW STATION)	• SIZE OF SOLAR LAMP ASSEMBLY	LARGE SOLAR SIZE AND BELOW HORIZON TRAVEL AREA ESTABLISHES 68 FT DIA DOME ENCLOSURE	• INTENSITY AND QUALITY OF SUN SIMULATION LIGHT CAN BE ACCOMPLISHED • WEIGHT OF UNIT MUST BE MINIMIZED
NO. 4 SUN MOVEMENT	• MECHANICALLY POSITIONED FROM SUNRISE TO SUNSET BY A PIVOTING AND ROTATING CARRIER ARM	• SOLAR SIZE AND WEIGHT (MOMENT OF INERTIA)	• SYNCHRONIZATION OF SOLAR MOVEMENT WITH FLIGHT CONTROLS • SOLAR SIMULATOR MASS	• COOLING SYSTEM WILL PRESENT UNRESTRICTED YAW ROTATION
NO. 6 DOME ENCLOSURE	• TRANSLUCENT 68' DIA. DOME/DIFFUSER FABRICATED WITH CAST JOINT SEAMS	• MAX. OPERATING TEMP. 200°F • MAX. RATE OF SURFACE TEMP. CHANGE 12°F/MIN. • FACILITY AREA SIZE – 100 X 100 X 80	• CONTROLS TO LIMIT THE TEMP. RATE OF CHANGE • STRUCTURAL QUALITY AND TRANSMISSION OF CAST JOINT	• SOME DEGREE OF PROTOTYPE FABRICATION IS REQUIRED TO ESTABLISH A CONFIDENCE LEVEL IN THE JOINT CASTINGS TECHNIQUES AND MATERIAL PROPERTIES . THIS WILL ESTABLISH THE REQUIRED COLOR AND DEGREE OF LIGHT TRANSMISSION/DIFFUSION, UNIFORMITY OF THE CAST JOINT, AND INTERIOR PROJECTION SURFACE.

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Table 1 External Illuminated Crew Station Design Facility Simulation Concept (Sheet 2 of 2)

TASK	A SIMULATION DESIGN APPROACH	B DESIGN LIMITATIONS	C SYSTEM INTERFACE PROBLEMS	D REMARKS
NO. 7 MOTION SIMULATION HORIZON LINE	MECHANICAL HORIZON LINE SIMULATION • PITCH • ROLL • YAW	• PHYSICAL LIMITING MOVEMENT $+/-30^{\circ}$ (BEARING TO PEDESTAL) • INPUT H.P. – ANGULAR VELOCITY • STRUCTURAL LIMITATIONS	• TERRAIN SIMULATION AND STRUCTURAL ARRANGEMENT • REDUCE MASS	R&D EVALUATION OF THE ACTUATORS SLIP RINGS AND COOLANT TRANSFER PRIOR TO FINAL DESIGN
NO. 8 TERRAIN SIMULATION HIGH/LOW AMBIENT	TRANSLUCENT HORIZON PAN UTILIZING SKY LIGHTING SYSTEM TO SIMULATE LIGHT LEVELS AND COLOR REFLECTANCE	• HIGH AMBIENT – NO VISUAL DETAIL FEATURES POSSIBLE • LIMITED TO REFLECTANCE INTENSITY AND COLOR RENDITION ONLY • LOW AMBIENT – LIMITED TO PROJECTED NIGHT SCENE AND TARGETS	• SYNCHRONIZATION OF HORIZON LINE AND SKY INTENSITY	SKY/EARTH CONTRAST AND TERRAIN COLOR DURING HIGH AMBIENT – REFLECTING FROM 7-70% OF THE SKY INTENSITY ONLY
NO. 9 REDUCED VISIBILITY FOG RAIN SNOW	FOG – OIL BASE FILTERED SYSTEM RAIN – TRANSPARENT DROPLET BEADS SNOW – POLYETHEYLENE FLAKES	WATER MAY NOT BE USED FOR ANY SIMULATION DUE TO MECHANISMS MOISTURE DAMAGE	• ACTIVATION OF HORIZON LINE IS LIMITED DURING FOG/CLOUD SIMULATION • CONTROL OF SIMULATION WITH FORCED AIR COOLING SYSTEM	R&D REQUIRED FOR RAIN SIMULATION, CONTROLLED INJECTION AND REMOVAL SYSTEM.
NO. 10 VISUAL EFFECT AIR TO AIR AIR TO GROUND FLARE	HIGH AMBIENT • AIR/AIR AIR/GROUND – NOT FEAS. DUSK & NIGHT • AIR/AIR & AIR/GROUND: PROJECTOR SYST. – CANNED, TERRAIN BD. COMPUTER GEN	HIGH AMBIENT – SAME AS TERRAIN LOW AMBIENT – PROJECTED NIGHT SCENE AND TARGETS: VIDEO PROJECTION, MOTION PICTURE } LIMITED BRIGHTNESS OF IMAGES	• SYNCHRONIZATION OF MOTION AND SCENE CHANGE	AIR/GROUND SIMULATION ARE FEASIBLE WITHIN LIMITATIONS CITED.
NO. 11 POWER SYSTEM	PROVIDE MULTIPLE SECONDARY UNIT SUBSTATIONS TO SATISFY THE FACILITIES ELECTRICAL POWER REQUIREMENTS. THE ELECTRICAL SYSTEM CAN BE EXPANDED/MODIFIED AS NECESSARY TO MEET FACILITY POWER REQUIREMENTS.		TO BE DETERMINED DURING DETAIL DESIGN OF FACILITY.	POWER SYSTEM CONFIGURATION ASSUMES THE AVAILABILITY OF A 13.8KV, 60 HZ UTILITY SYSTEM WITH A ~14 MEGA WATT CAPACITY.

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CSDF MODULAR CONCEPT APPROACH

A modular construction philosophy can be followed in the fabrication of crew station design facility in the event total funding is not available. However, a comprehensive design of the complete environmental lighting simulator is recommended prior to fabrication of modular components. This is necessary to insure that all components work in harmony and that simulator capabilities added late in the sequence of facility development are not compromised by modular components installed at the beginning of facility development.

Figure 6 helps illustrate the modular design concept approach that can be followed and establishes the minimum basic lighting system required to generate the ambient luminance that would be experienced in an aircraft crew station under actual flight conditions.

The basic lighting simulation system would consist of:

- Sky lighting system and support structure
- Solar systems
- Dome enclosures
- Temperature controls
- Computer control system
- Power

The modular additions for a completed facility would consist of:

- Horizon and motion systems
- Terrain simulation systems
- Visual effects systems
- Reduced visibility systems
- Additional control system elements

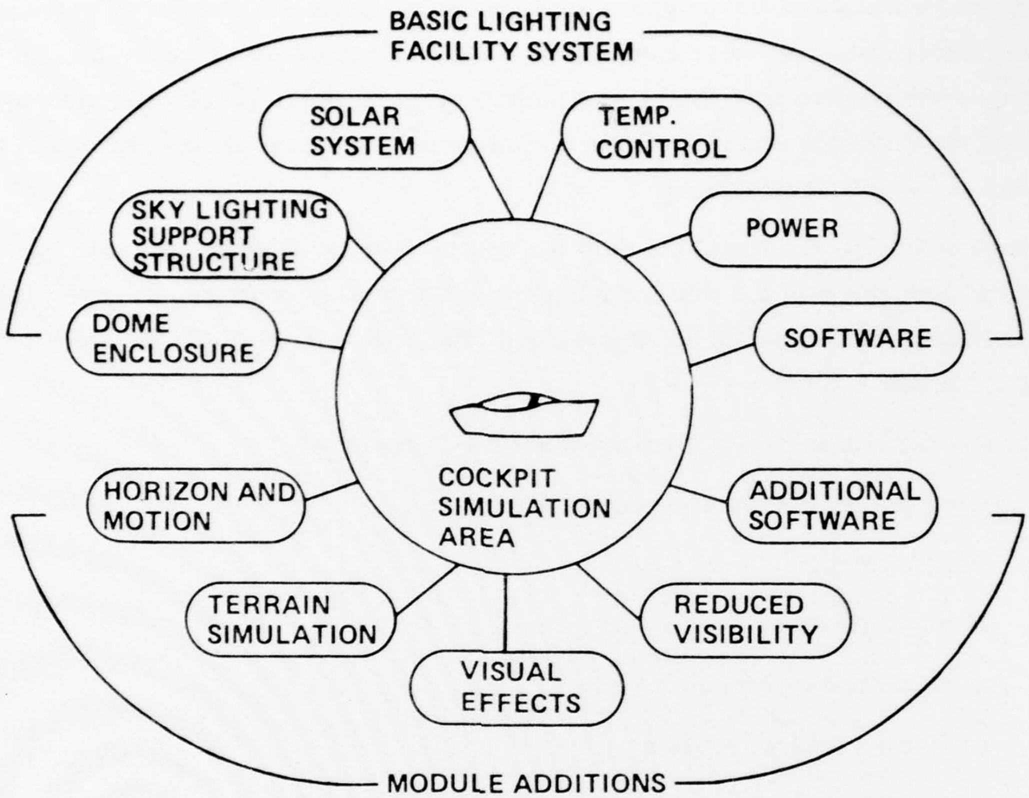

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Figure 6. CSDFS Modular Concept Approach

SECTION II

BASELINE CONFIGURATION DEVELOPMENT

PHYSICAL REQUIREMENTS AND CONSTRAINTS

A number of important physical requirements and constraints were developed from the visibility (field of view) requirements and the crew station arrangements. The visibility requirements generally defined the regions where simulation equipment could be located and the cockpit variations defined the dimensions of the solar simulator.

Sky Illumination

The basic visibility requirements illustrated in Figure 7 generally apply to all cockpit configurations. For over-the-side visibility the single place cockpit, or two place tandem, establishes the requirement while over-the-shoulder visibility must be based on the two place tandem cockpit. The reduced requirement over the nose will not substantically relax the simulation requirements. For a fixed base simulator the terrain can be represented by a screen which is rotated and tilted to simulate aircraft motion or by suitably changing the projection of sky, horizon and terrain on a fixed screen.

In general, the illumination problem in the internal sky simulator system arrangement (shown in Figure 8) is based on visibility requirements only; these requirements limit the available volume for illuminators. The illuminators are at different levels in the sphere. The volume above and behind the cockpit must be used with care because it creates shadows from the solar simulator. The solar simulator could be constrained from going around the rear of the cockpit with obvious loss of direct panel illumination. In addition the sky, horizon and terrain projection would have to be accomplished with the illuminators marked A through E. Calculations showed that the high sky luminance required luminaires to virtually fill the entire volume shown as A through E in Figure 8. When requirements for effects projectors and shadowing by the cockpit are considered the available volume becomes marginal and very substantial technical projection problems are encountered.

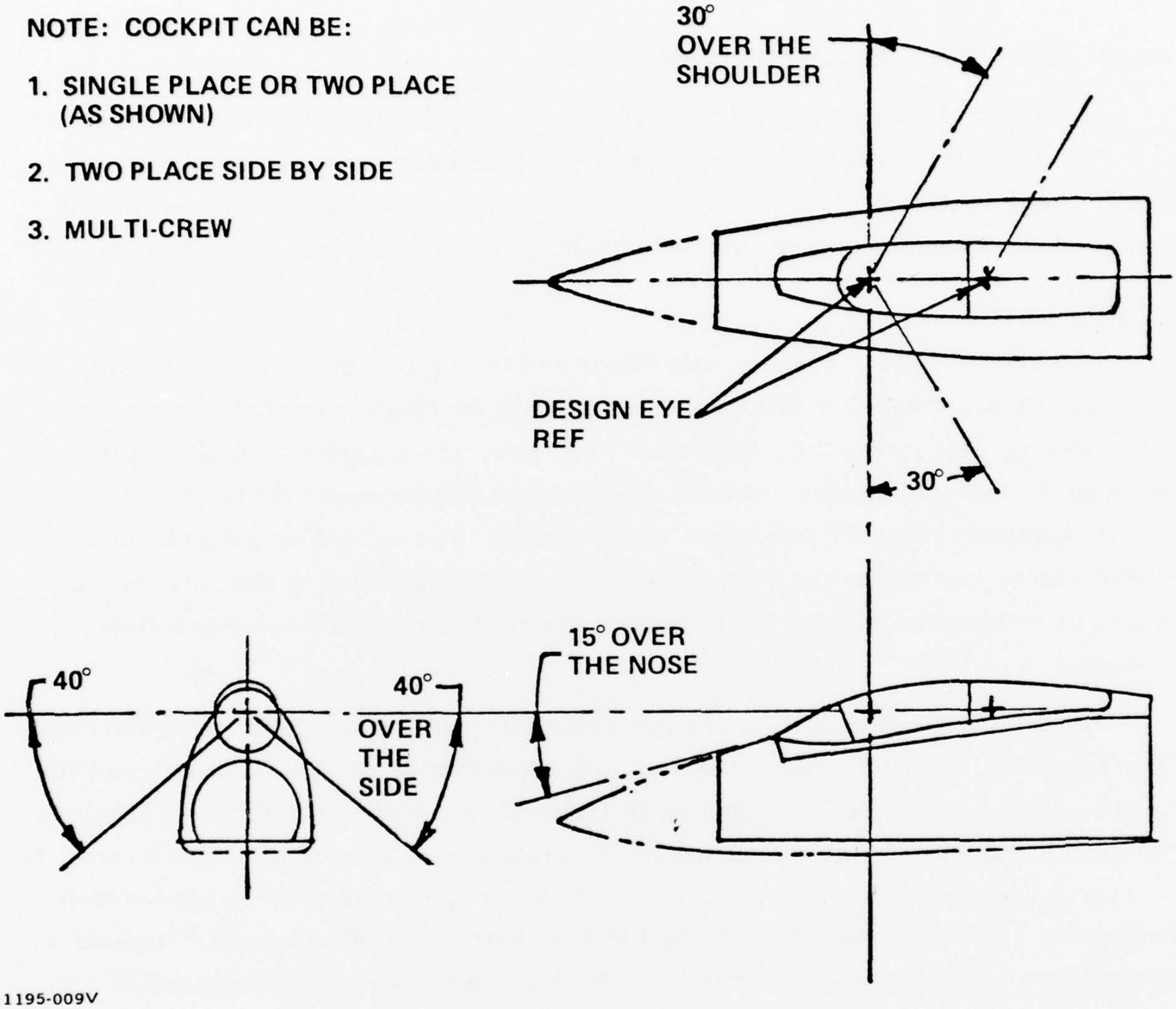

Figure 7. Typical Field of View Requirements

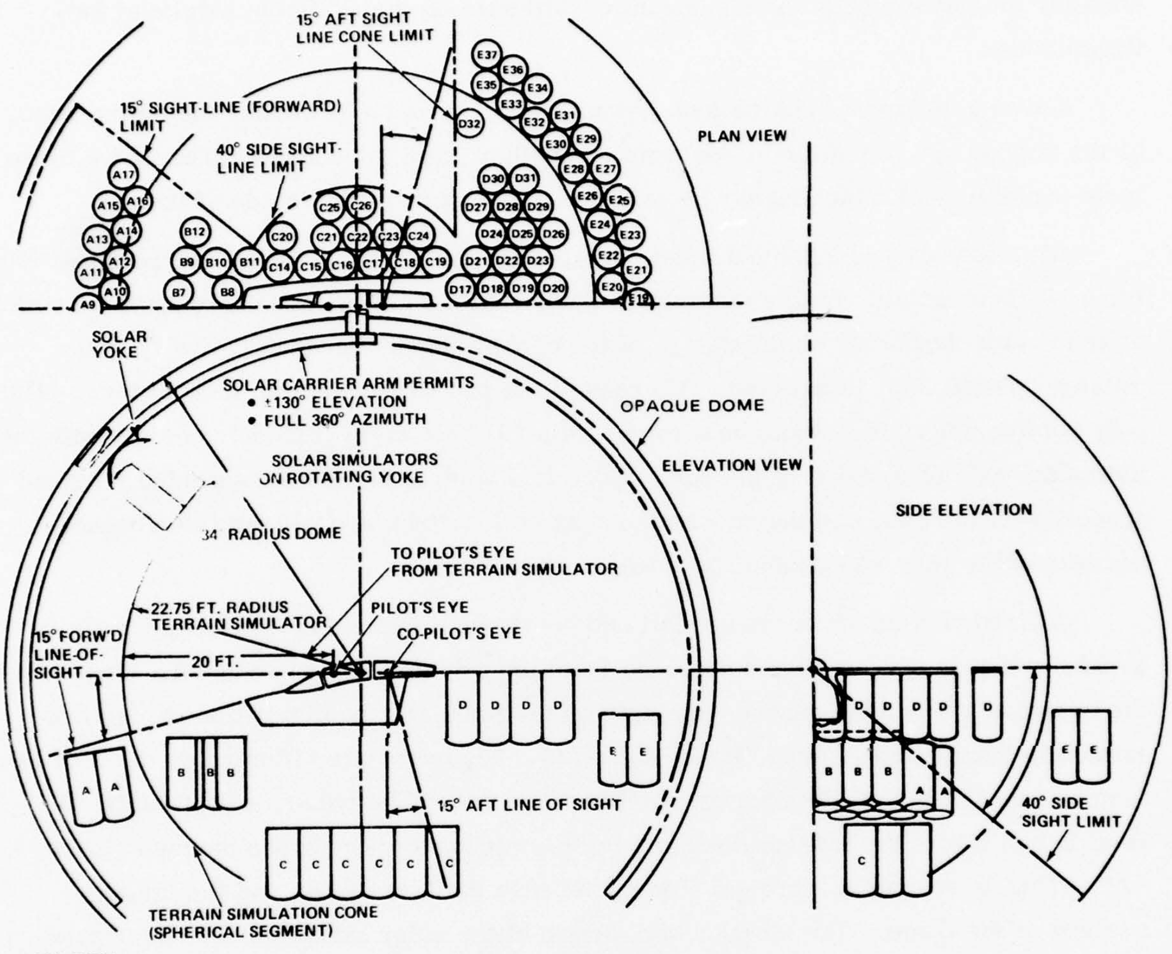

Figure 8. Internal Sky Simulator System

If the motion is simulated by moving a screen it should be continuously rotatable in azimuth plus a substantial angle in pitch and roll. In this case the screen becomes a pan which is articulated to simulate aircraft motion. Visibility to the pan and clearance for the pan gimbals has a substantial influence on the available locations for illuminators.

Given a 40° over the side look down capability, and a 30° bank, the entire area of the terrain pan is visible at one time or another from the cockpit. Therefore there is no possibility of attaching sky or terrain illuminators to the inside of the pan.

This is shown in Figure 9 where the dashed lines outline the terrain pan position for a 30° bank angle. In this position, a portion of the gimbal assembly could be visible over the side depending on the design of the cockpit support pedestal. As the pan rotates through 360° in azimuth, all areas of the pan will come into view in turn. The only volume not visible would be a cone with a 20° half angle (shaded), coaxial with the azimuthal axis of rotation of the pan. Since this volume is inside the gimbal ring and travels with the pan, nothing substantial may be located there without interference between cable runs and gimbal structure.

A fixed volume aft of the cockpit and below the elevation of the cockpit rails is available if it is supported and serviced from the cockpit support pedestal. However, the extent of the volume depends strongly on the simulator configuration; an approximation is illustrated as area "B" in Figure 10. Figure 10 also illustrates the additional volumes available for illuminators outside of the pan. The volume swept out by the terrain pan limits the available volume for illuminators to the cross hatched region "A". This is roughly a torroidal volume between the terrain pan and the interior surface of the dome. The location and motion of the solar simulator will be described later. However, the cross hatched volume "A" must be reduced if realistic sunset conditions are to be simulated. The solar simulator volume marked SS in Figure 10 would be removed all around the top of the torroid. The volume "B" could not extend above the cockpit rails if shadows are to be avoided when the "sun" is behind the cockpit.

Sky illumination may also be accomplished with external lamps shining through a translucent dome or a combination of internal plus external lighting. The external illumination approach will be described later in the report. However, there are no

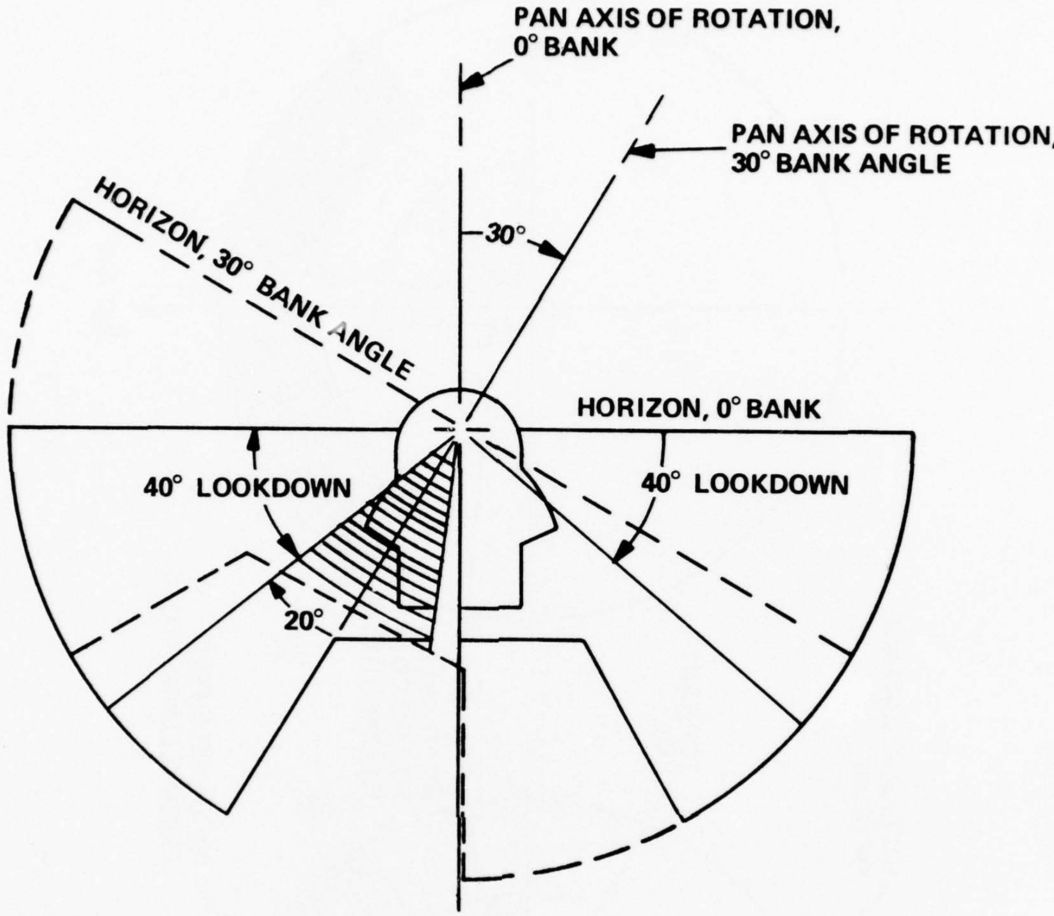

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Figure 9. Terrain Pan Visible Area With A 30° Bank and 40° Over The Side Lookdown

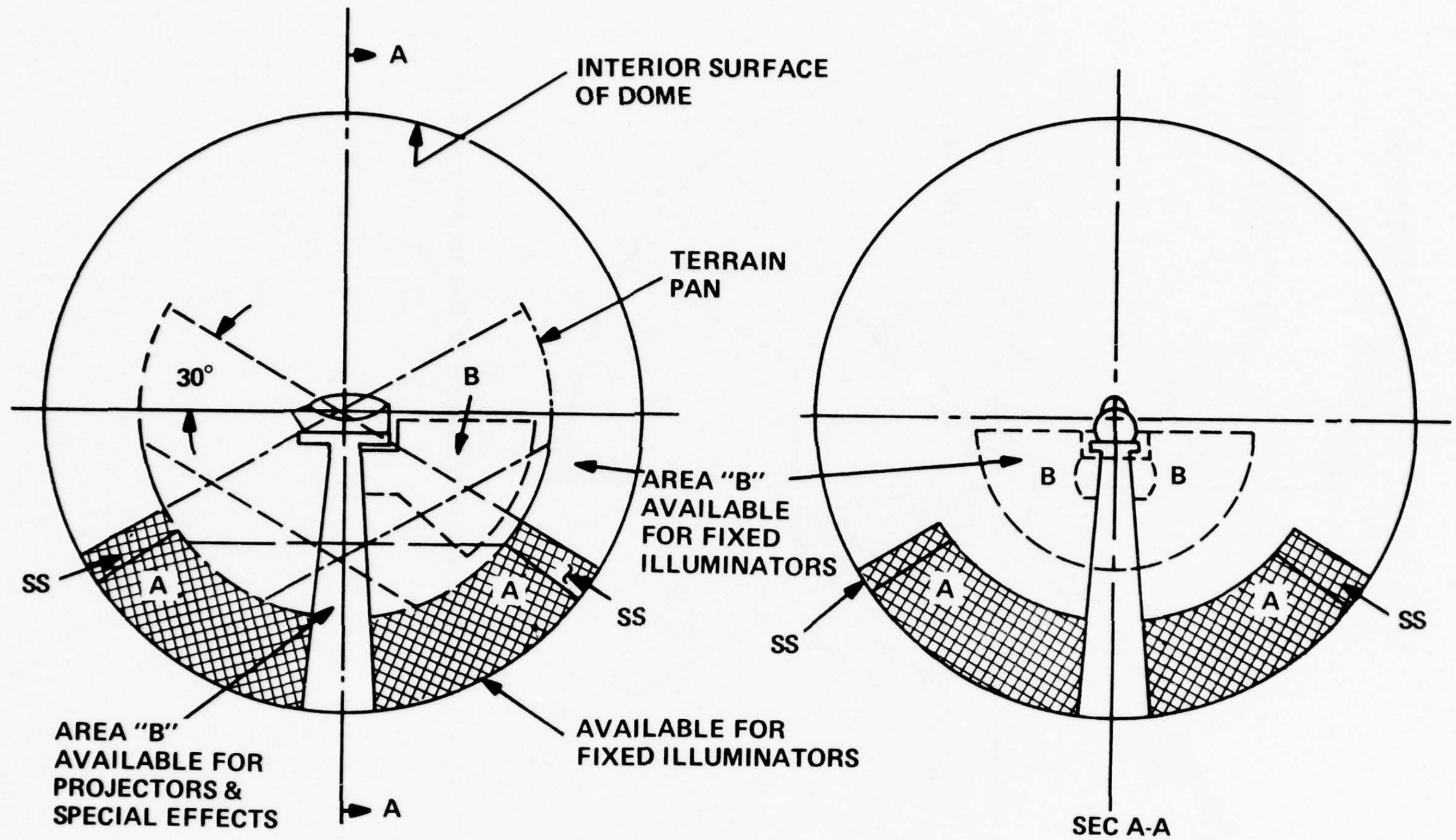

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Figure 10. Volumes Available For Internal "Sky" Illuminators in a Fixed Base Simulator

physical location problems for sky illuminators vis-a-vis the pan geometry with external illuminators. A system could combine external illuminators with a translucent dome and the internal illumination possibilities illustrated in Figures 10 and 8.

Variation of Sky Illumination

When fixed illuminators are used with a fixed base cockpit and a translucent terrain pan the relative appearance of the sky must be programmed to change with aircraft attitude. If an opaque terrain pan is used to generate the terrain and horizon, the magnitude of the programming is reduced but it is still required. If programming is not implemented with the translucent terrain pan, the sky luminance at the horizon will frequently appear to change with aircraft attitude. Use of a translucent terrain pan establishes the requirement for rapidly and uniformly varying the output of individual illuminators. It also constrains illuminator design to be capable of uniformly changing illumination all around the dome.

If sky luminance and color programming is to be avoided, internal dome illumination is the only alternative. In this case the illuminators occupying volume "A" in Figure 10 would have to move with the pan to insure realistic terrain luminance and color with aircraft attitude changes. The logistics for supplying power, and probably cooling fluid, would restrict the azimuthal freedom desired in the simulator. In addition to this major design deficiency the moment of inertia for the pan and structure would be substantial.

Feasible Sky Illumination Alternatives

Allowing for the anticipated requirements of other subsystems there are two feasible alternatives for simulating the sky. In both cases the sky brightness must be programmable to coincide with aircraft attitude changes.

The first alternative is:

- Externally mounted illuminators covering the dome
- Translucent outer dome
- Supplemental illuminators in volumes "A" and "B" shown in Figure 10

The second alternative is:

- An opaque dome
- Illuminators in volume "A" and "B" shown in Figure 10

Solar Simulation

The variation in cockpit geometries and the distance from the crewman's eye to the collimator are the major physical factors affecting the solar simulator. To provide a sunrise or sunset condition the solar simulator must be located beyond the terrain pan. The inner terrain pan surface would be at least 20 feet from the pilot's eye. This distance will determine the allowable collimation limits which in turn drive the size of the solar simulator.

Motion Limits

Relative Aircraft accelerations and motion limits were established for baseline purposes as:

Acceleration about pitch axis	=	1 rad/sec^2
yaw axis	=	1 rad/sec^2
roll axis	=	4 rad/sec^2

The maximum angular excursion was established by estimating the practical limits set by the mechanical structure associated with a fixed base cockpit. The limits are:

About Pitch axis	$\pm$ 30 deg
About Roll axis	$\pm$ 30 deg
About Yaw axis	Unlimited

Size of Dome Enclosure

Two factors combine to establish the minimum dome enclosure size. They are the minimum visual simulation distance and the nature of the simulated sun rise and sun set.

Minimum Visual Simulation Distance

Minimum visual distance is established by human factors. Crew perception limits in visual effects simulation requires 20 feet optimum distance from the pilots eye reference point to all non collimated objects to enhance binocular effects and reduce operator fatigue.

In visual simulation, distant screens (dome shaped projection surfaces in the case of the CSDF) should be presented with the eyes accommodated for infinity. A resting eye has a depth of field of 20 feet to infinity. For objects not at infinity, accommodations and convergence vary with the distance to the object.

At low luminances (e.g., 0.015 foot lamberts) equivalent to a moonlit and starlit clear night, the average resting focus of the eyes is about 1.7 diopters or to the tip of your arm (Reference 34). The eye does not accommodate to viewing distance even if it varies from 0.3 meters to infinity. Thus, in night scenes, if the screen distance is moved in from 20 feet towards the observer, the image will start to appear sharper (in focus) as the constant focal distance of the eye is approached. In effect the perception will be incorrect as compared to that in the real world.

At higher luminances (e.g. 15.0 foot lamberts), the focal distance of the eye varies almost proportionately with the viewing distance (2.75 diopters at 0.35 meters and 0.5 diopters at infinity). Now if the screen distance to the eye is reduced, the response time of the eye, when going from viewing cockpit instruments to external viewing in the outside world, would also be reduced. Thus behaviorial data (i.e. crew performance) collected in such simulations would be in error (i.e. visual focus response times would be shorter than in the real world) and could lead to improper experimental conclusions.

In a side-by-side cockpit, where the pilot's and co-pilot's eyes are separated by several feet, the parallax error (displaced direction of an object as seen by the two pilots) will increase as the screen distance is reduced. For example, if the two pilot's eye reference points are 3.5 feet apart, and the screen distance is 20 feet, the parallax in viewing the same position on the screen is 10 degrees. If the screen distance is reduced to 15 feet, the error is increased to 13.5 degrees. At 10 feet screen distance, the error is 20.05 degrees. Even the 20-foot screen distance is not optimal for this situation. In the outside world, an object at 1000 feet from the pilots would have only a 1/5-degree (12 minute of arc) parallax between the pilots.

Simulated Sunrise/Sunset

Solar system elevation travel affects the diameter of the dome depending on whether the sun sets on the horizon or is allowed to set fully below the horizon as shown in Figure 11. The solar simulator resting on the horizon will permit a dome enclosure of 22 feet radius. Allowing the solar simulator to rise or set below the horizon would require additional travel clearance area and increase the dome radius to a minimum of 34 feet.

Visible Horizon Line

In order to simulate aircraft real-time attitude changes and maneuvers, it is necessary to change the perceived locations and orientation of the sky/ground horizon in relation to cockpit. The horizon line can be generated by projecting on the dome wall or by mechanically manipulating an edge or screen.

Extensive engineering research has been conducted to establish a visible horizon line under all ambient conditions of day and night. The areas of visual display technological investigations were:

- Projected systems using television or canned film
- Point light sources
- Laser TV projector
- Projected computer generated images.

The main problem that exists in generating a real world scene (horizon line) for the CSDF with all the systems investigated is, of course, the high ambient lighting under which this scene must be generated. The magnitude of all of the other real problems (field of view, stereoscopic perspective, resolution, etc.) pales by comparison with the problem of generating a scene of sufficient brightness for use in an ambient lighting situation where illumination ranges from 200 to over 10,000 foot lamberts. Several mechanically generated motion approaches that were studied are shown in Figure 12 and summarized in Table 2.

It is an accepted principle in the visual simulation field that the brightness of a projected image must be higher than that of the background onto which it is superimposed. Motion picture projectors produce approximately 100-foot-lambert

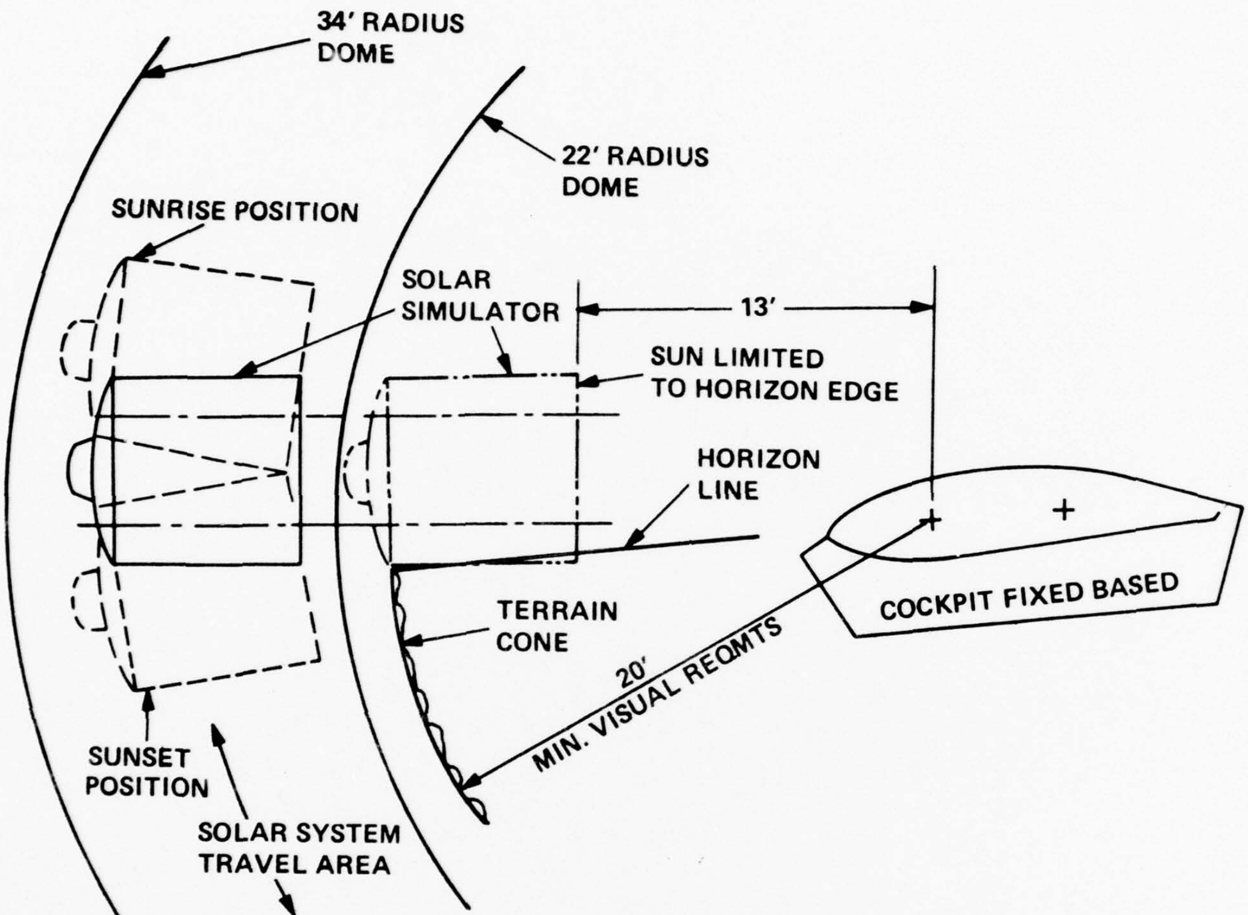
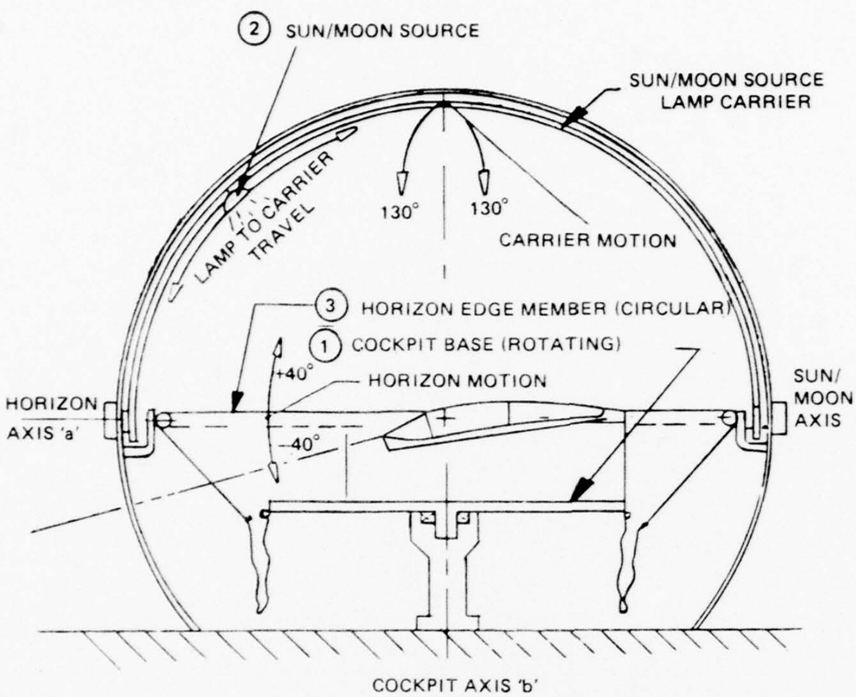


Figure 11. Effect of Sun Limited to Horizon for a Reduced Dome

MOTION SIMULATION

APPROACH METHOD #1



1. Cockpit Base Rotation

   Cockpit will be capable of rotating 180° about a vertical axis only.

   To maintain visual realism during rotation, a full 360° domed sky/terrain surface is required.

2. Sun/Moon Positioning

   Sun/moon lamp unit tracks along the full length of a semi-circular carrier beam that pivots about a fixed horizontal axis 'a'.

3. Horizon Edge Member

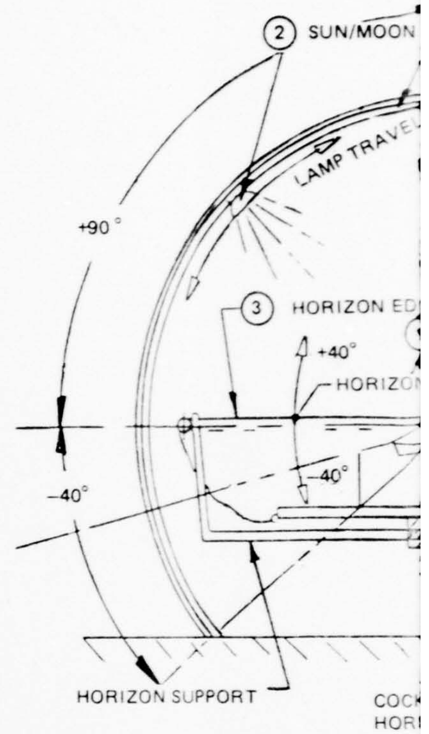
   Circular horizon edge member pivots about a fixed diametrical horizontal axis 'a'.

   A combination of the cockpit base rotating about its vertical axis 'b' and horizon povitong about its horizontal axis 'a' will provide visual simulated pitch, roll and turn maneuvers with respect to the horizon.

   By co-ordinating sun/moon lamp movement along the track and the carrier movement about the horizontal axis 'a', the position of the sun relative to the cockpit can be correctly maintained during these maneuvers.

MOTION SIMULATION

APPROA



1. Cockpit Base Rotation

   Cockpit will be capable of rota
   only.

   To maintain visual realism duri
   sky/terrain surface is required.

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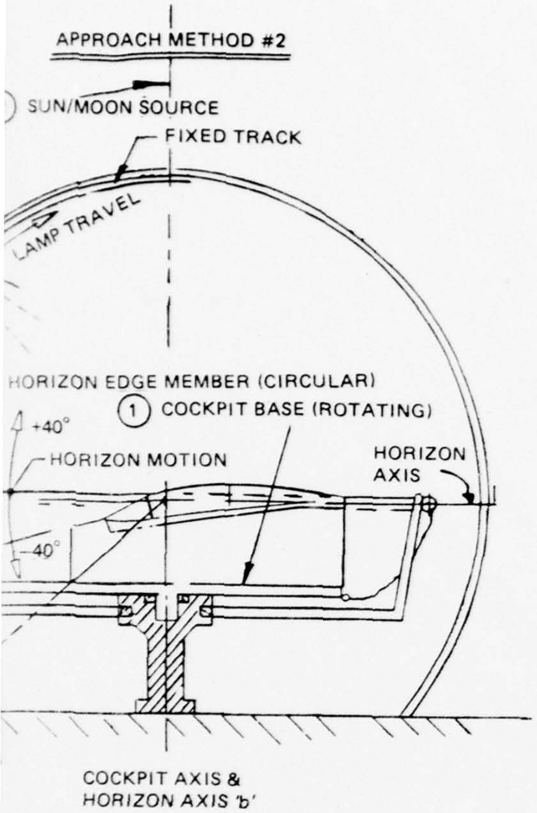
   Sun/Moon lamp unit can travel
   along a fixed track in a vertical plane

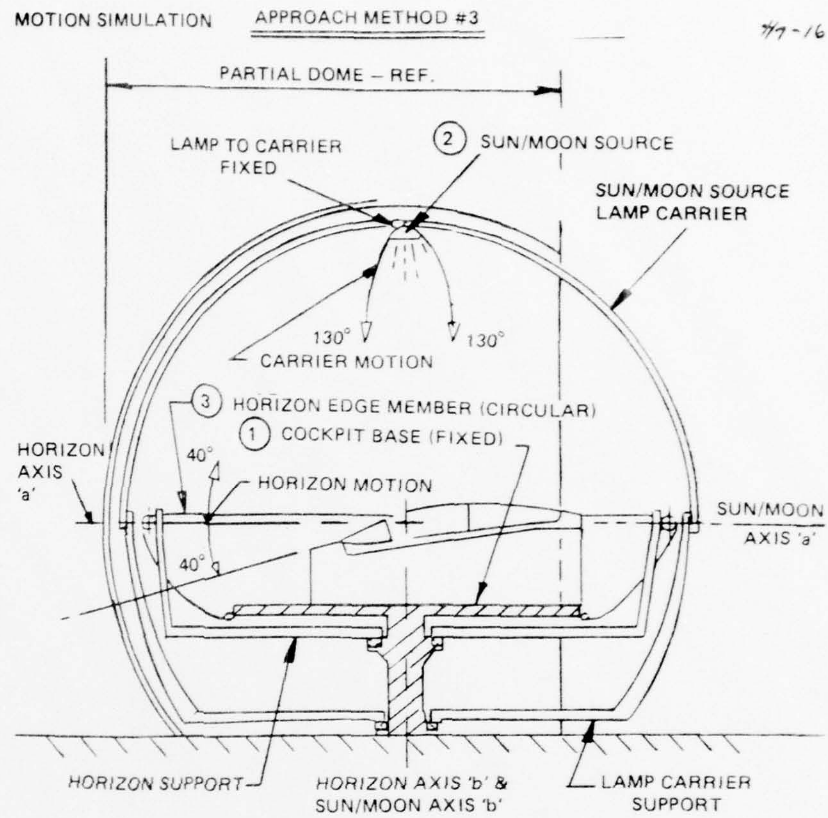
   A combination of the cockpit
   will provide visual simulated pitch, r
   respect to the sun.

3. Horizon Edge Member

   Circular horizon edge member
   axis 'a' and rotates about a central v

   This allows the visual pitch, rol
   relation to the sun position to be co-
   horizon position.





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l realism during rotation a full 360° domed
quired.

nit can travel from -40° to $+90^{\circ}$ from the horizontal
vertical plane.

the cockpit base rotation and sun/moon tracking
ated pitch, roll and turn maneuvers with

dge member pivots about a horizontal diametrical
t a central vertical axis 'b'.

ual pitch, roll and turn maneuvers executed in
ion to be co-ordinated with respect to the

1. Cockpit Base – Fixed

   Sky simulation using a fixed base cockpit and a 30° aft over the shoulder visibility would require a partial dome.

2. Sun/Moon Positioning

   Sun/moon source is fixed at the center point on a semi-circular carrier beam.

   Carrier beam pivots about a horizontal diameter axis 'a'

   Carrier beam support rotates in a horizontal plane about a vertical axis 'b'

   Simultaneous motion about both axes provides visual simulation of roll, pitch and turn maneuvers of the cockpit with respect to the sun/moon source.

3. Horizon Edge Member

   Circular horizon edge member pivots about its horizontal diametrical axis 'a' and its support rotates about its vertical axis 'b'.

   This allows the visual pitch, roll and turn maneuvers executed in relation to the sun position to be co-ordinated with respect to the horizon position.

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Figure 12. Motion Simulation

brightness within practical projection distance. In view of the fact that motion picture projections are perhaps the brightest large scene projectors available, the generation of a real world scene in the CSDF does not appear feasible with state-of-the-art simulation technology.

The present state of the art as determined by thorough investigation precludes projection as a realistic horizon/terrain simulation in the high ambient lighting conditions. Using the latest techniques for visual presentation of the out-the-window scene would necessitate the dimming of the background lighting to relatively low levels. This would compromise the purpose of the CSDF which is to provide realistic ambient lighting levels.

The design approach for a visual horizon line under day ambient intensity must be a movable mechanical edge member against an illuminated surface.

SIMULATOR BASELINE ALTERNATIVES

Design concepts suitable for a baseline system were screened early in the program in accordance with the study plan illustrated in Figure 2. Each concept was evaluated in terms of its ultimate performance and the physical requirements to implement the concept. In general, the major drivers of the configuration are the generation of the horizon line and the mechanization of the sun/moon simulator. The simulation of sky brightness is a technological challenge, but it does not drive the size of the simulator dome or the major mechanical features of the simulator.

Preliminary Design

Several mechanically generated horizon motion approaches that were studied are illustrated in Figure 12. In each approach the pilot's design eye is positioned on the horizon plane. Aircraft altitude is simulated by raising the cockpit on the pedestal or lowering the horizon line mechanism.

A visual circular edge is provided as the horizon line. This is an opaque or translucent surface which is illuminated by sky light and/or backlighted to provide the desired ground luminance and horizon reference. The mechanical approach was necessary because there are no projection methods that will provide simulated realistic levels of sky brightness. The combination of features that characterize the approaches in Figure 12 are shown in Table 2.

Table 2 Relative Motion of the Cockpit Horizon, and Sun/Moon

METHOD	COCKPIT	HORIZON	SUN/MOON	GIMBAL MOTION
1	ROTATES ABOUT VERTICAL AXIS	TILTS ABOUT HORIZONTAL AXIS	180 DEG	PIVOT ABOUT HORIZONTAL AXIS
2	ROTATES ABOUT VERTICAL AXIS	TILTS ABOUT HORIZONTAL AXIS AND ROTATES ABOUT VERTICAL AXIS	90 DEG	FIXED
3	FIXED	TILTS ABOUT HORIZONTAL AXIS AND ROTATES ABOUT VERTICAL AXIS	FIXED	PIVOTS ABOUT THE HORIZONTAL AXIS AND ROTATES THE VERTICAL AXIS.

For approach 1, the horizon tilts about a horizontal axis and the cockpit rotates about the vertical axis. This provides the entire range of cockpit to horizon/terrain orientation, but it complicates the problem of presenting terrain features. To keep the sun or moon in the proper orientation, the collimator travels along a track through 180+ degrees relative to the cockpit and the track pivots about a horizontal axis. In the second approach, the solar simulator track is fixed and the simulator translates through 90+ degrees. The horizon/terrain screen tilts about a horizontal axis and rotates about the vertical axis. Cockpit rotation is also necessary. The cockpit and the solar simulator are both fixed in approach 3. The horizon implementation is the same as for approach 2 and the support arm for the solar/moon collimator pivots about a horizontal axis and rotates about the vertical axis.

Each of these approaches provided insights into the simulation problem and guided the evolution toward the final baseline configuration. This configuration is shown in Figure 13.

Selected Baseline Simulator

The mechanical arrangement of the selected baseline simulator is illustrated in Figure 13. In the baseline system the cockpit is supported in the center of the dome by a pedestal. The cockpit is essentially fixed because its only motion is vertical to simulate aircraft altitude. The change in height of the pilot's eye reference point (or increase in cockpit pedestal height) required to simulate increasing altitude is shown in Figure 14. This Figure also illustrates horizon depression angle and corresponding altitude for altitudes of 1,000 to 100,000 feet. This motion is not expected to unduely increase the design complexity or the physical line runs to the cockpit. However, the horizon depression angle is significant and must be accounted for in the simulator.

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The horizon/terrain assembly is independently supported from the floor by a mechanism containing six hydraulic actuators. The hydraulic actuators provide motion to the assembly about 2 axes in the horizontal plane. Rotation about the vertical axis is provided by a bearing assembly at the top of the support structure. Electric motors are the baseline actuators for horizon/terrain rotation.

The solar/moon simulator and support gimbal are carried on the horizon/terrain mechanism. As the horizon/terrain mechanism is actuated to simulate aircraft altitude changes, the relative position of the sun or moon will be correctly maintained.

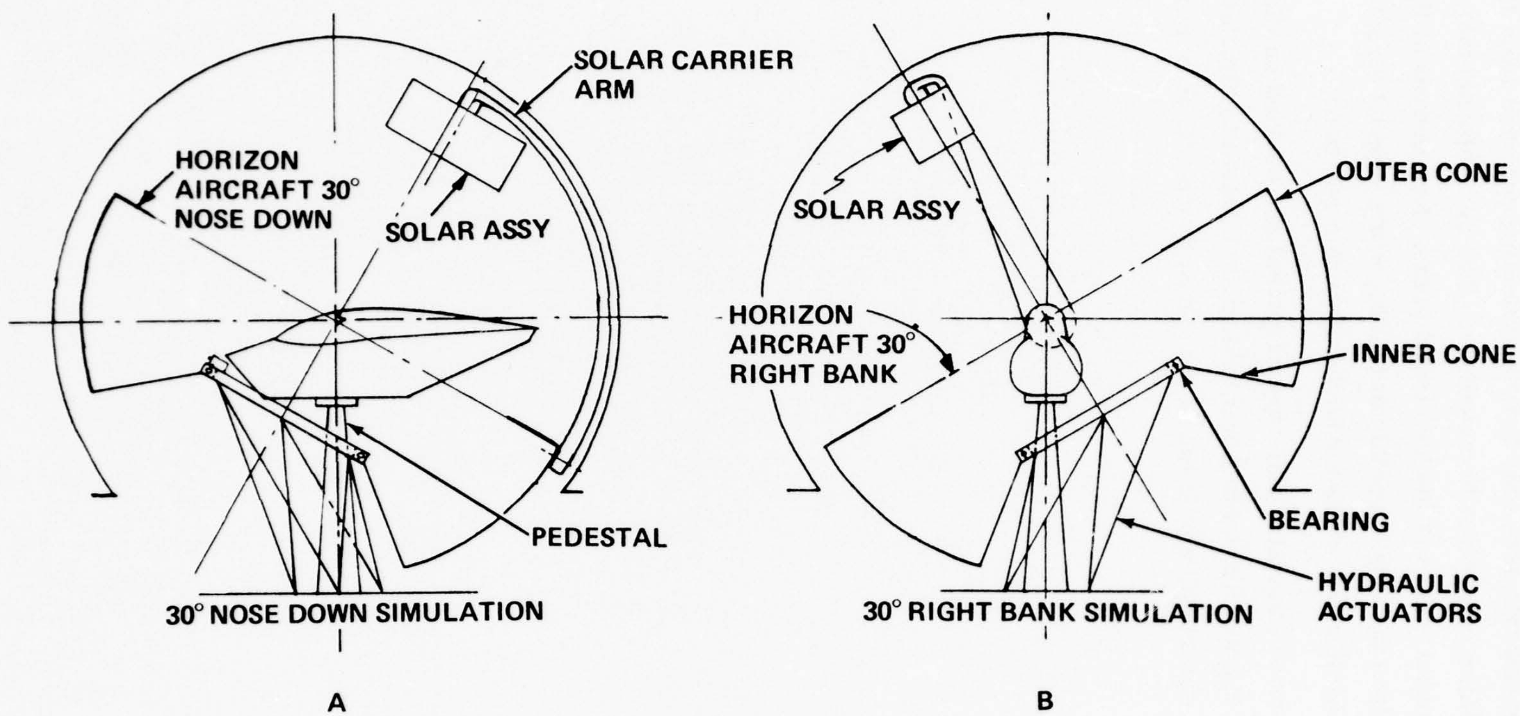

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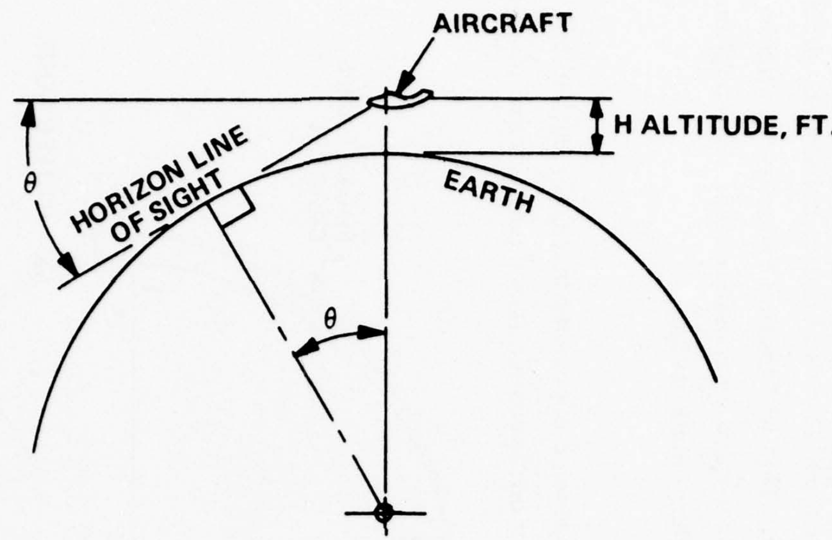
Figure 13. Motion Simulation Baseline Concept



ALTITUDE H, FT.	DEGREES	* RELATIVE COCKPIT HEIGHT INCREASE INCHES
1,000	0.56	2.3
5,000	1.25	5.2
10,000	1.77	7.4
25,000	2.79	11.7
50,000	3.95	16.6
75,000	4.84	20.3
100,000	5.58	23.4

* PILOTS EYE 20 FT TO HORIZON LINE

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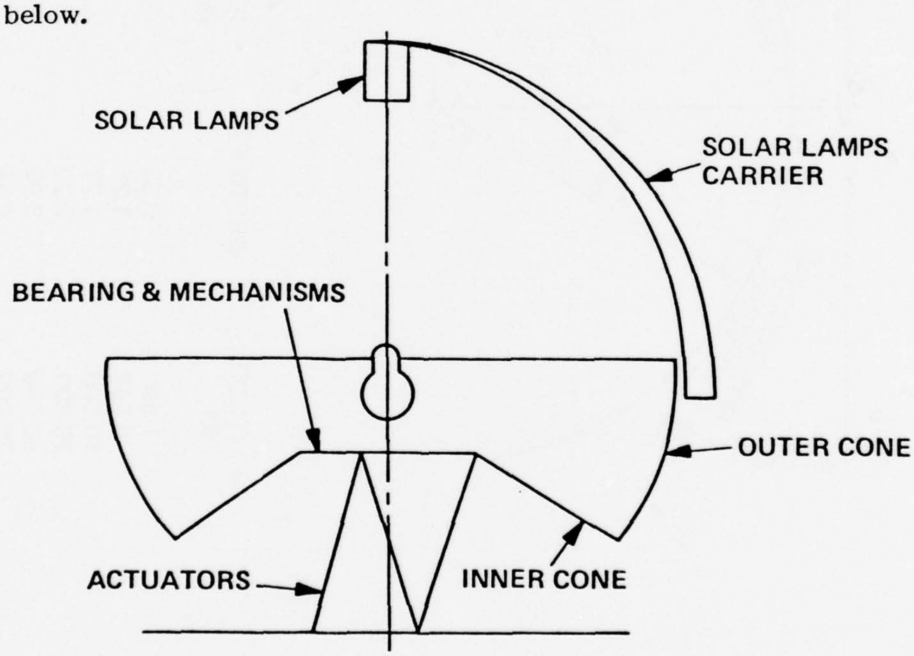
Figure 14. Horizon Depression Angle vs Altitude

The only solar/lunar motions will be related to the time of day simulation and not aircraft motion. Time of day is simulated by rotating the lunar/solar support arm about an axis in the horizontal plane. Maneuvering displacements will be ± 30 degrees about the horizontal axis and 360 degrees or more about the vertical axis. Continuous rotation of the horizon/terrain mechanism is considered a good possibility in this configuration. There are no large torque requirements on the horizon/terrain mechanism for sun/moon motion and signal transmission can be minimal. Consequently, slip rings can be considered to transmit electrical power for the solar/lunar simulator across the bearing. Cooling for the solar simulator can be accomplished by distributing the heat exchanger along the support arm. This will increase the air conditioning load on the dome, but the aximuthal freedom is a valuable consideration. The implementation of this feature is naturally subject to further detail design.

Estimated Weights

Weight estimates assigned to the various components that contribute to the maneuvering inertia of the work statement configuration (fixed cockpit) are identified and listed below.



COMPONENTS	WT ESTIMATE (LB)
SOLAR LAMPS	1200
SOLAR LAMPS CARRIER	1050
OUTER CONE	1200
INNTER CONE	800
BEARING & MECHANISMS	5200

Table 3 Torques Due to Inertia (ωF^2)

$T = I\alpha$

$I = mr^2 = \frac{w}{g} r^2$

PITCH TORQUE: $T_{yy} = I_{yy}\alpha_{yy}$

ROLL TORQUE: $T_{xx} = I_{xx}\alpha_{xx}$

YAW TORQUE: $T_{zz} = I_{zz}\alpha_{zz}$

	1	2	3*	4	5*	6	7	8	9	10	11
ITEM	EST WEIGHT (LBS)	MASS(M) = w/g = (1) /32.2	$\bar{r}_{xx}$ and $\bar{r}_{yy}$ (FEET)	$\bar{r}^2_{xx}$ and $\bar{r}^2_{yy}$ = (3)	$\bar{r}_{zz}$ (FEET)	$\bar{r}^2_{zz}$ = (5) 2	I xx and I yy = (2) x (4)	I zz = (2) x (6)	Txx (ROLL) = 30.55 x (7) FT LBS	Tyy (PITCH) = 1.91 x (7) FT LBS	Tzz (YAW) = 1.91 x (8) FT LBS
SOLAR LAMPS STRUCT & EQUIP.	1200	37.27	23.0	529	23.0	529	19716	19716	602318	37657	37657
SOLAR LAMPS CARRIER	1050	32.61	21.7	471	21.7	471	15359	15359	469217	29336	29336
OUTER CONE	1200	37.27	20.0	400	18.4	339	14908	12632	455439	28474	24127
INNER CONE	800	24.84	16.0	256	11.4	130	6359	3228	194269	12146	6166
BEARING AND MECHANISMS	5200	161.49	8.67	75	6.0	36	12111	5814	370014	23132	11104
TOTAL							68453	56749	2091257	130745	108390

*$\bar{r}$ ASSUMES MASS CONCENTRATED AT THIS RADIUS (FT)

AXIS - xx = ROLL AXIS
AXIS - yy = PITCH AXIS
AXIS - zz = YAW AXIS

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Estimated Torques

Torque estimates for the various motion system components are shown in Table 3. Calculations for the motion actuator sizes are shown in Table 4 and Table 5. Hydraulic pump flow, pressure, and horsepower calculations are also included in Table 5. These calculations are based on the achievement of peak maneuvering rate at midstroke. This design aspect equalizes acceleration and deceleration operating torques on the horizon/terrain mechanism.

Table 4 Torque Requirements

MOTION ACTUATORS:

ACTUATOR SIZE REQUIRED MAXIMUM TORQUE ABOUT X-X AXIS

ACTUATOR ARMS TO X-X AXIS HORIZON AT 0°

2 ACTUATORS	69.5 IN. EACH	= 139
2 ACTUATORS	101.5 IN. EACH	= 203
2 ACTUATORS	30.0 IN. EACH	= 60
TOTAL ACTUATOR ARMS		= 402.0 IN. = $X_{ACT.}$

ACTUATOR FORCE REQUIRED = $F_{ACT.}$

$$\Sigma M_{x\text{-}x} = 0 = T_{xx} - F_{ACT.}(X_{ACT.})$$

$$0 = 2{,}091{,}257 \text{ FT LB } (12 \text{ IN.}) - F_{ACT.}(402)$$

$$F_{ACT.} = \frac{25{,}095{,}084}{402} = 62{,}426 \text{ LB}$$

ASSUME OPERATING PRESSURE = 1,800 PSI

ACTUATOR AREA REQUIRED = 62,426/1800 = 34.68 IN.^{2}

ACTUATOR ARM TO X-X AXIS, HORIZON AT 30°

2 ACTUATORS	126 IN. EACH	= 252
2 ACTUATORS	64 IN. EACH	= 128
2 ACTUATORS	21.25 IN. EACH	= 42.5
TOTAL		422.5 IN.

THIS ACTUATOR EFFECTIVE ARM IS LARGER THAN ABOVE. THEREFORE ACTUATOR IS SIZED FROM NEUTRAL (0°) HORIZON.

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Table 5 Actuator Lengths

ACTUATOR LENGTHS

FULLY RETRACTED = 137″
FULLY EXTENDED = 213″
NEUTRAL = 151″
STROKE = 76″

$\left.\begin{array}{l}\\ \\ \\ \end{array}\right\}$ TRAVEL = 62″

VOLUME OF OIL REQUIRED TO GO 30°

2 ACTUATORS TRAVEL 62″ EACH = 124″

2 ACTUATORS TRAVEL 14″ EACH = 28″

2 ACTUATORS TRAVEL 9″ EACH = 18″

TOTAL STROKE - 6 ACTUATORS = 170″

V = STROKE X AREA; $\therefore$ V = 170 (34.68)
V = 5896 in^3

$T = 2t;\ \&\ \phi = \frac{1}{2}\, a\, t^2$

$\therefore t^2 = \frac{2\phi}{\alpha}$

$\phi = .262$ RAD; & $a = \frac{30.55 \text{ RAD}}{\text{SEC}^2}$

$t^2 = \frac{2(.262)}{30.55} = 0.0172 \text{ SEC}^2$

t = 0.131 SEC

T = 2t = 0.262 SEC

HYDRAULIC PUMP FLOW Q IN^3/SEC

$$Q = \frac{V}{T} = \frac{5895}{.262} = 22503 \text{ IN}^3\text{/SEC}$$

$$\frac{22503 \text{ IN}^3 \text{ (60 SEC)}}{231 \frac{\text{IN}^3}{\text{GAL.}} \text{ SEC MIN}} = 5845 \text{ GALLON/MIN}$$

ASSUME PUMP PRESSURE = 2,000 psi

$$\text{HP REQUIRED OUTPUT} = \frac{\text{GPM X PSI}}{1714} = \frac{5845\ (2000)}{1714} = 6{,}820 \text{ HP}$$

$$HP_{IN} = \frac{HP_{OUT}}{(0.9)\ (0.9)} = \frac{6{,}820}{(0.81)} = 8{,}420 \text{ HP}$$

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SECTION III
SKY SIMULATION

Sky simulation involves the simultaneous satisfaction of several requirements in terms of luminance and color. If any characteristic can be applied to the appearance of the sky, it is variability. All luminance ranges will be encountered from 10^{-4} foot lamberts (FL) to 10^{4} FL, with a variety of associated sky colors. The range in sky luminance measured by the University of California Visibility Laboratory is documented in Appendix A. A summary of the data they provided is contained in Table 6 for four general conditions. Scans for two of these conditions are illustrated in Figures 15 and 16. They are for flight under an overcast and under broken clouds. Under an overcast, the sky luminances and terrain luminances are relatively uniform regardless of the azimuth of scan. Under broken clouds, there is a much larger variation. When the photometer was pointing toward the sun (zero degree azimuth), the large peak was recorded. For the other azimuth angles, the luminances are much lower. The general envelope of the lower values represents clear sky, and the local peaks are presumably clouds.

The data provided by the Visibility Laboratory was taken at relatively low altitudes. At higher altitudes, the clear sky luminance will normally decrease. The predicted relative luminosity versus altitude is shown in Figure 17, using sea level as a base. This reduction is applicable at the zenith, but not always at the horizon. At higher altitudes, the data in Table 6 would be applicable towards the horizon but the zenith values would be reduced by the factor in Figure 17. In addition to the reduction of zenith luminance with altitude, the sky color will be shaded from a "white" on the horizon to "blue" at the zenith. The luminance values in the statement of work constitute a reasonable description of the maximums found in nature.

In the course of the study, it was found necessary to separate the generation of clear sky luminance from cloud effects. In general, an acceptable sky simulation can be achieved if the CSDF has the following capability:

- Clear sky luminance provided from 10^{-4} to 2.5×10^{3} FL with appropriate variations from zenith to horizon. At the highest luminance values, the sky would be "white." The blue sky characteristic of very clear days or

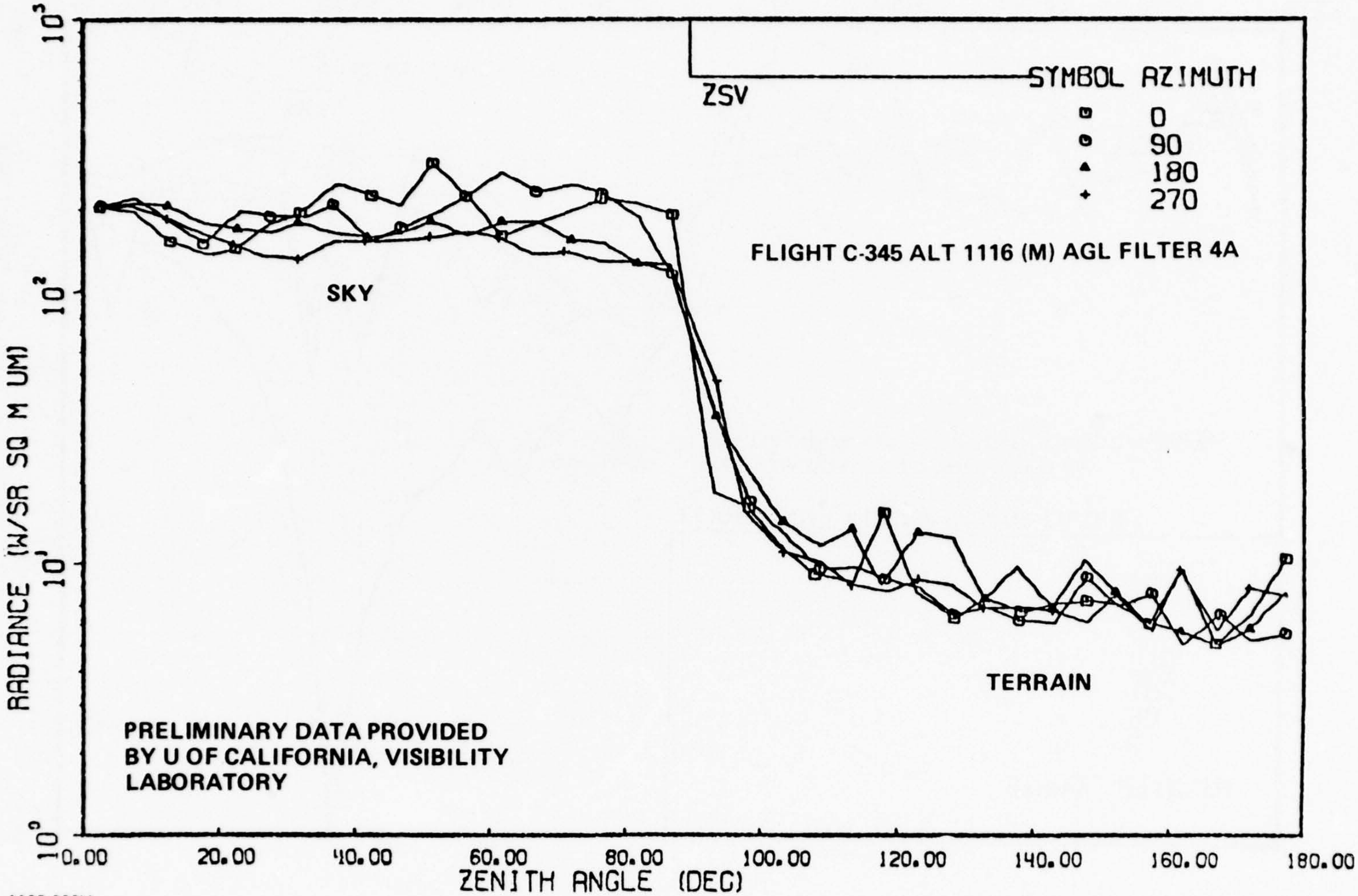

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Figure 15. Measured Sky and Terrain Luminances

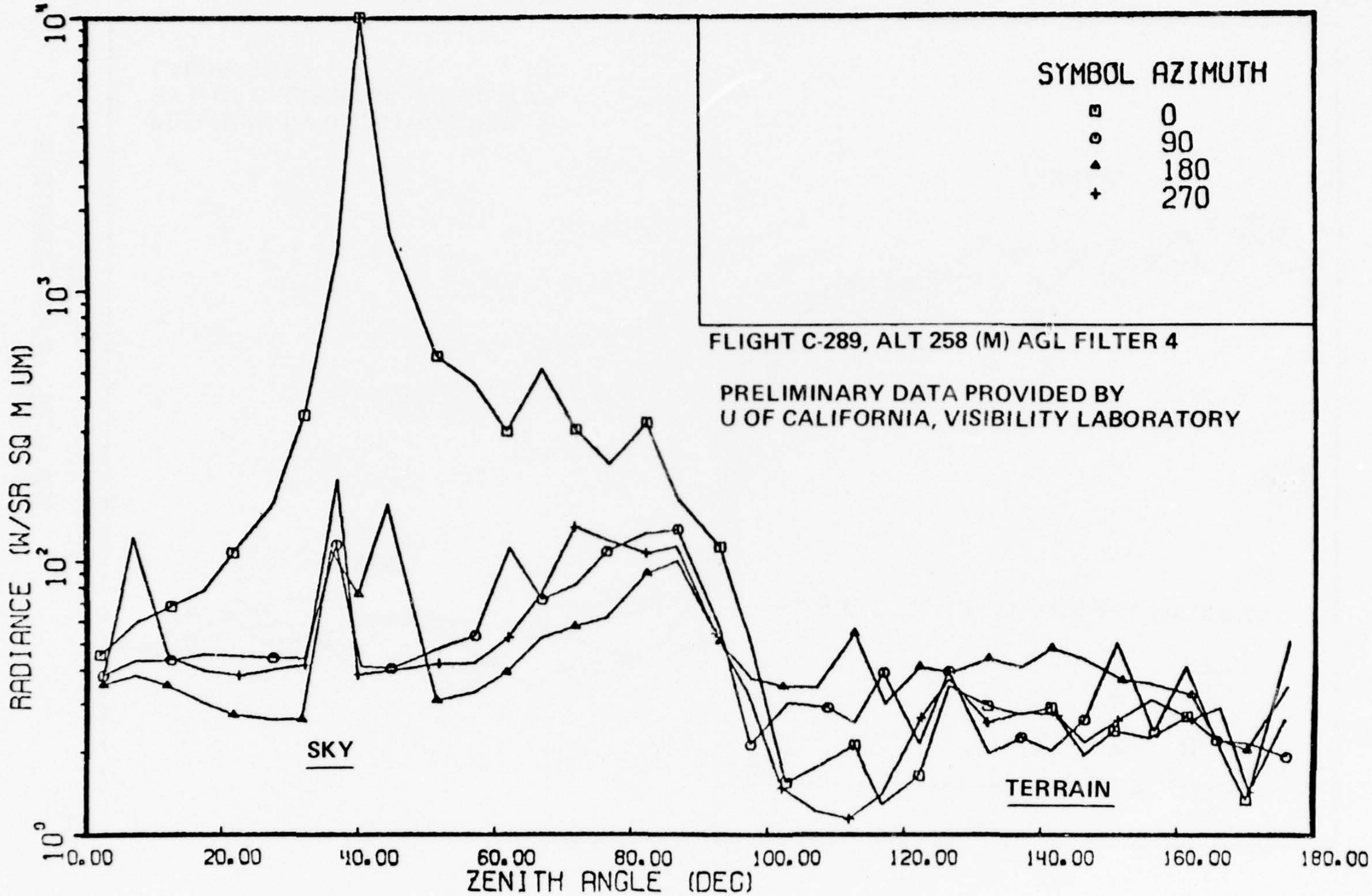

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Figure 16. Measured Sky and Terrain Luminance

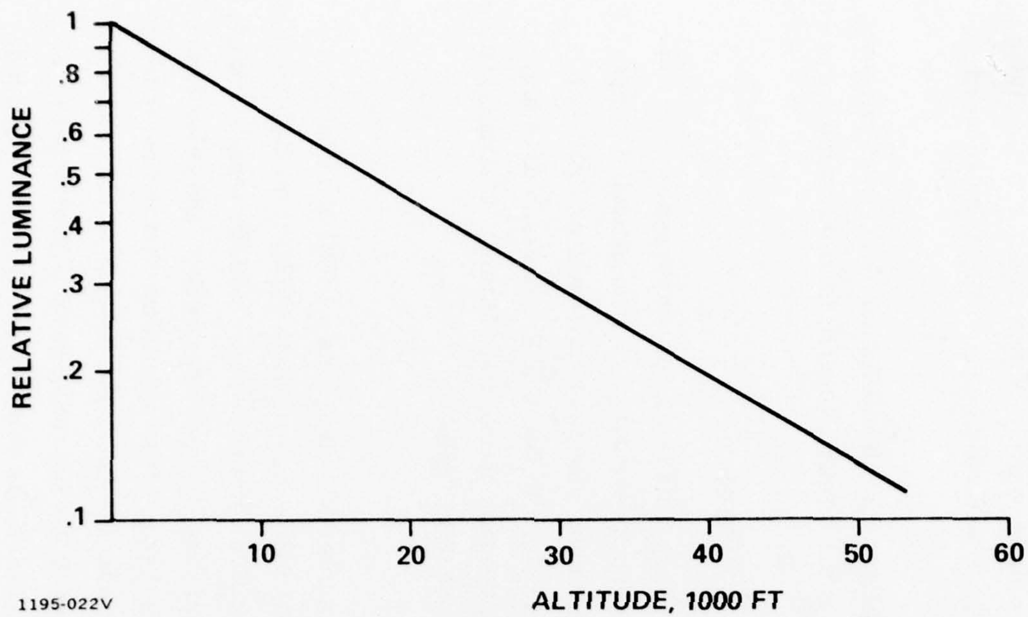

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Figure 17. Relative Change of Clear Sky Luminance with Observer's Altitude

FLIGHT	DESCRIPTION	ALTITUDE (M AGL)	HORIZON SKY (CROSS OR DOWN-SUN)	ZENITH SKY	NADIR TERRAIN
C-360B	CLEAR	1143 500	3070 - 1960 2250 - 1740	1170 - 769 1300 - 913	724 - 523 756 - 231
C-354	UNDER OVERCAST	1116 549	3860 - 2410 3780 - 1490	4620 - 4050 5980 - 4450	216 - 108 325 - 115
C-151	CLEAR	4422 726	3460 - 1290 4560 - 2390	286 - 221 435 - 330	748 - 567 340 - 239
C-289	UNDER BROKEN CLOUDS	1192 258	4450 - 2350 2770 - 1900	10800 - 643 2560 - 739	865 - 525 1060 - 279

1195-023V

Table 6 Summary of Luminance Ranges in Foot-Lamberts high altitude should be available at appropriate luminance levels. When the simulation approaches sunset or twilight, a reddish sky is feasible at appropriately reduced luminance.

- Cloud formations simulated separately from clear sky simulation by projecting the cloud formation over the luminous sky. The resulting cloud luminance and color would be the sum of the two effects. The most demanding cloud simulation would be the 10^4 FL requirement. At this level, the cloud would only be white. Where clouds are simulated at sunset, a range of reddish tones could be provided at the reduced luminance levels.

The optical and mechanical provisions for controlling color are a major consideration in the design but should not affect the CSDF logistics to the same degree as the high white luminances required.

AVAILABLE LAMPS AND SPECTRAL EMISSIONS

A number of candidate lamps were identified by a literature search and consultation with the manufacturers or their representatives. The principal lamps which provide the high luminance values must also provide a "white" light. To secure a range of luminance values and colors in the CSDF, the luminaires may contain a mix of lamps by type and wattage plus appropriate filters. Characteristics of some of the larger sources are described in Table 7.

Metal Halide Lamps

The spectral radiance of the Osram metal halide lamps (HMI) and sunlight is compared in Figure 18. The lamp emission is very close to sunlight through the visible region. This spectrum is applicable within ±10 percent of the lamp's intended operating point. A relative plot of luminance, power consumption, and color temperature is shown in Figure 19 for the HMI Lamp. It is significant that the color temperature of the HMI lamp rises as the luminance falls, the reverse of the common Tungsten Lamp. This is one of the reasons the operating point is restricted to a ±10 percent variation. As the lamp gets blue, its commercial utility is impaired. However, for sky simulation purposes, this may be a useful feature. The lamp will become progressively more blue as the voltage is continuously lowered. This could

Table 7 Type of Lamps Evaluated

LAMP	POWER WATT	LUMINOUS FLUX AT LIFE BEGINNING ℓm	LUMINOUS EFFICIENCY ℓm/w	APPROXIM. COLOR TEMP °K	SPECTRUM	LIFE HRS.	BURNING POSITION	SAFETY AND OTHER OPERATIONAL CONSTRAINTS
TUNGSTEN HALOGEN (DICRO-DAY LIGHT NSP PAR 64)	1,000	19,400*	19.4	5200	CONTINUUM	200	ANY	NO SPECIFIC CONSTRAINTS OR SAFETY REQUIREMENTS
METAL HALIDE (OSRAM) HMI	1,200	110,000	92	EQUIVALENT TO 5800	CONTINUUM (DENSELY PACKED LINE SPECTRUM)	750	ANY	WARM UP TIME: 3.4 MIN, RESTART TIME: UP TO 10 MIN AC OPERATE & BALLAST REG.
FLOURESCENT (DAY-LIGHT)	215	12,000	80	EQUIVALENT TO 4800	LINE	12,000 —	HORIZONTAL	BALLAST REG
XENON (SHORT ARC)	20,000	800,000	40	6000	CONTINUUM WITH IR SPIKE AT 8000A	1,000	VERTICAL (ANODE UP) TO HORIZONTAL	REQUIRE: WATER COOLING PRESSURIZED – POSSIBLE EXPLOSION, OZONE GENERATION DUE TO UV
	30,000	1,320,000	44	6000	CONTINUUM WITH IR SPIKE AT 8000A	1,000		

NOTES: 1. EVALUATION BASED ON LITERATURE SEARCH AND LAMP MANUFACTURER'S CONTACTS: BERKEY COLORTRAN, GE, WESTINGHOUSE, SPECTROLAB, OSRAM, DUROTEST CORPS. NORELCO AND OTHERS.

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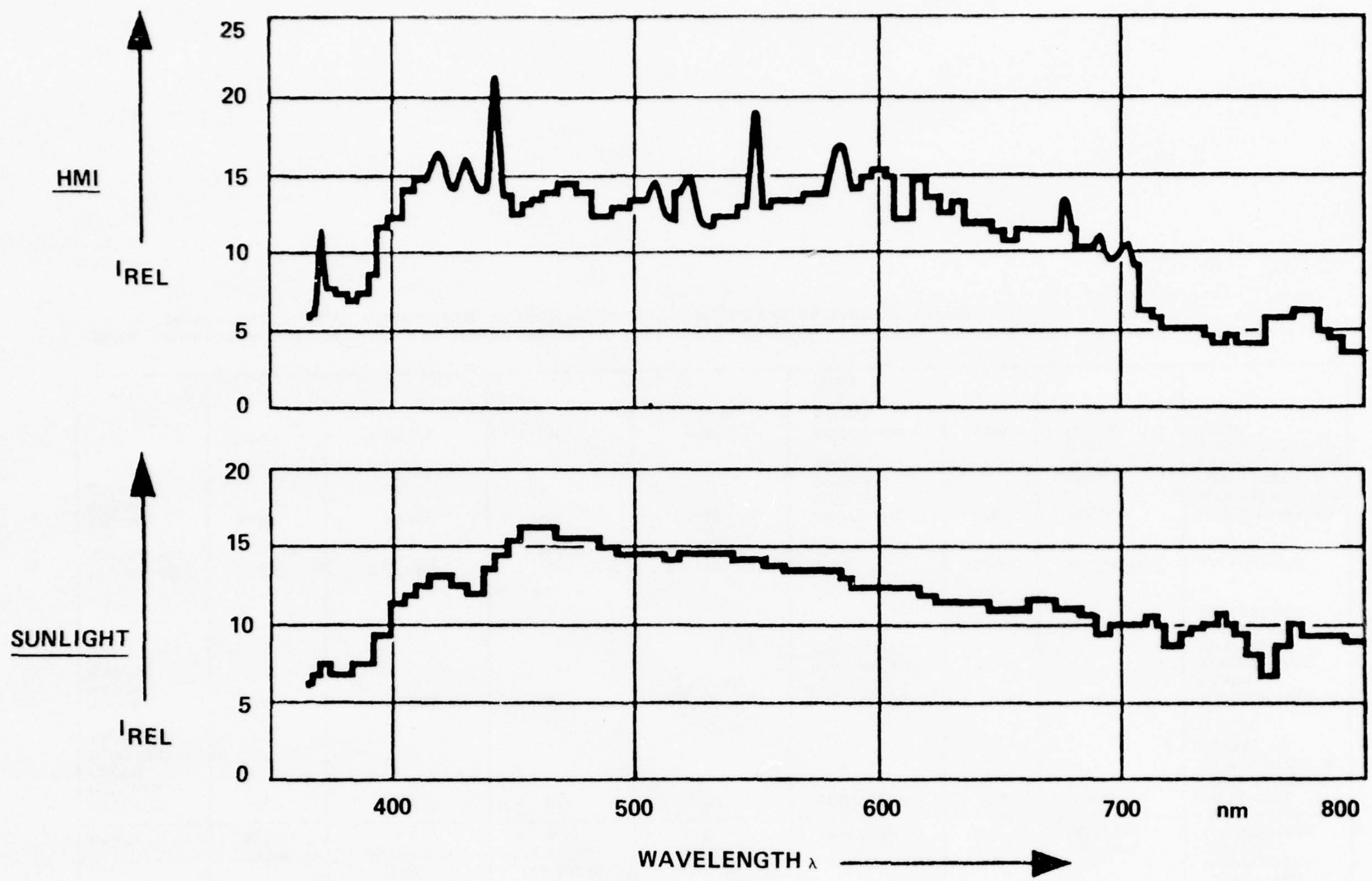

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Figure 18. Relative HMI Spectral Distribution vs Daylight

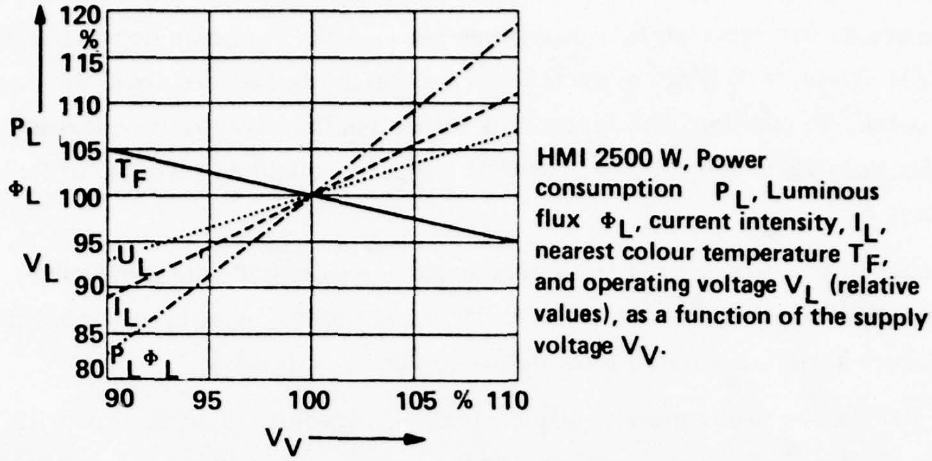

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Fig. 19 Relative HMI Performance vs Supply Voltage

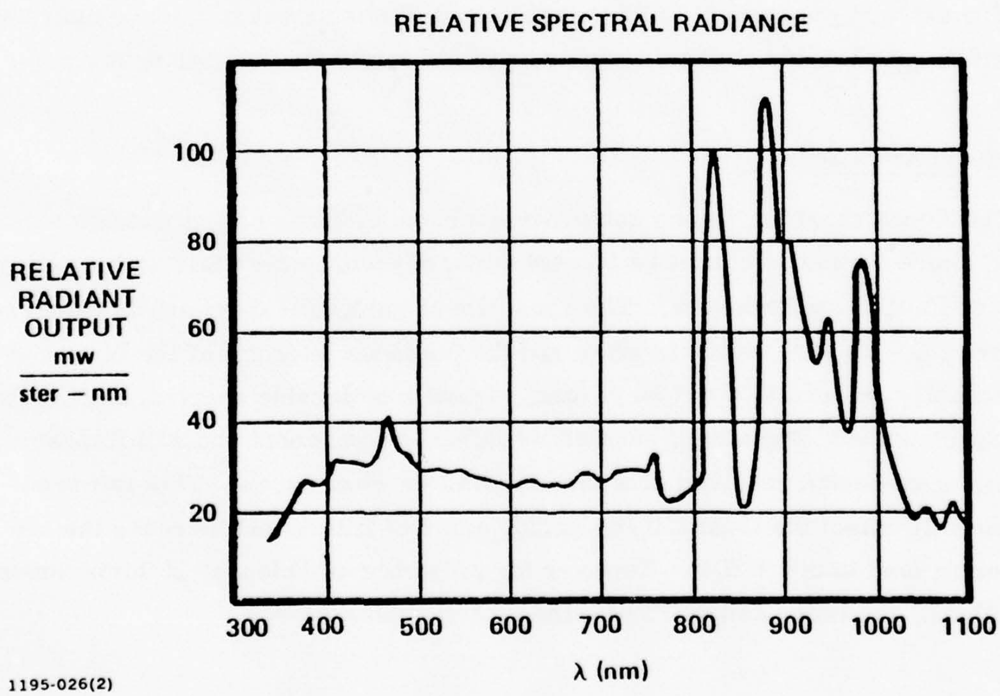

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Figure 20. Typical Measured Irradiance from a Xenon Short Arc Lamp

be utilized to vary the saturation of blue available from the lamp and a filter. The manufacturers do not endorse this procedure because the variation between lamps, which always exists, will become greater as the voltage is reduced from the design operating point. In addition, the lamps will extinguish themselves at different reduced voltage. This characteristic of HMI lamps is considered worthy of further investigation.

Because of the decrease in color temperature associated with increased emission of the HMI lamp, a color shift to "warmer" tones must be expected if the lamp is driven harder to maintain its luminous output as it ages.

The HMI lamps are commercially controlled from full output to zero with mechanical shutters. They are reported as not having thermal problems with the mechanical shutters because virtually all of the HMI radiation is in the visible region. The substantial infrared radiation associated with a Xenon lamp, for example, is not present.

Daylight Fluorescent Lamps

The daylight fluorescent is clearly the most efficient, but it must be operated horizontally and its line emission spectrum is not conducive to filtering for color effects.

Xenon Short Arc Lamps

The Xenon short arc lamps can provide a huge luminous output and are most suitable where the lamps cannot be located uniformly within the CSDF and the dome acts as an integrating enclosure. The spectrum of the Xenon short arc is illustrated in Figure 20. Its appearance is white and the luminous intensity of the lamp can be electrically reduced to about 50 percent without a noticeable spectral shift. The Xenon spectrum contains a very substantial infrared component and will impose more stringent design requirements than the HMI or Fluorescent. This infrared radiation will affect the feasibility or performance of filters and increase the air conditioning load in the CSDF. However for projection of "clouds" at luminances up to 10^4 FL, the large Xenon lamp is the best available source.

Preferred Lamp Usage

For the translucent dome, the choice is:

- HMI for clear sky simulation, with appropriate color filters
- Xenon short arc lamps for overprojection of cloud effects.

For the opaque dome, the choice is:

- Xenon lamps for clear sky simulation, with appropriate color filters
- Xenon for cloud effects.

In both cases, smaller, less demanding, lamps would be used for fill-in and for special effects at low luminances.

EXTERNAL ILLUMINATION SYSTEM

The concept described and illustrated here serves to scope the problem and define the requirements for hardware development. A detailed design phase would be necessary to define the geometry and operating details of the luminaires. In turn, this would be expected to follow a proof-of-concept demonstration that would be performed at reduced scale.

A generalized section through the dome and a group of luminaires is shown in Figure 21. In concept, the luminaires are closely packed around the exterior of the dome, separated by a distance A from the dome. The lower extremities of the luminaires are quadrilaterals approximating squares, with the length of Side D, to provide contiguous coverage over the dome. The lower extremity of the luminaires should be readily formed as the shape of the quadrilateral changes for different positions on the dome. The upper portion of the luminaire would be identical for all luminaires, and it would contain the lamps, filters, and a mechanical lamp intensity control, plus a diffusing shield.

The walls of the luminaire have a high reflectivity (R_L). If the reflectivity is diffuse rather than specular, the interior of the luminaire will represent the interior of an incomplete integrating sphere. There will be uniform illumination as long as the observer cannot look directly at the lamp. Since uniform illumination is essential for clear sky simulation, this approach was adopted to determine feasibility without

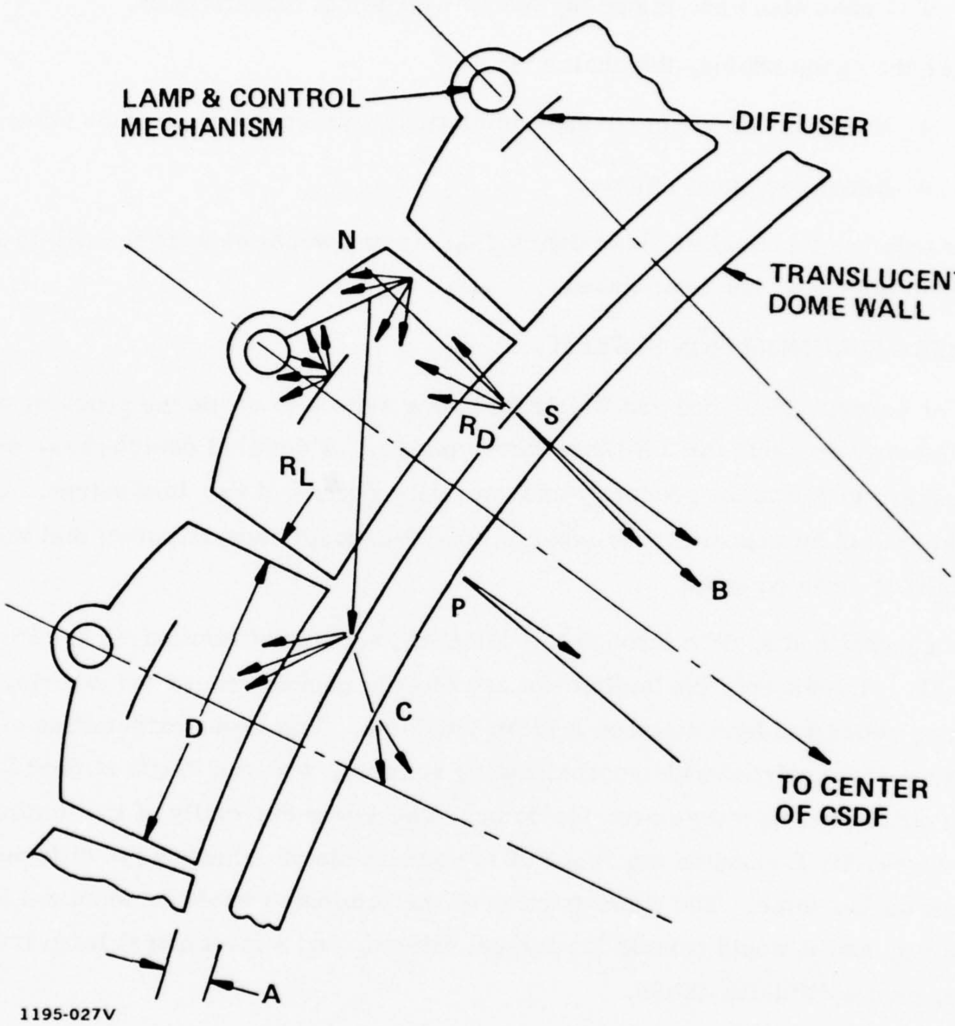

Figure 21. Generalized Sky Luminaire Concept for External Illuminators

prejudice to specular reflection. It will be shown that the dome wall should be translucent and if the translucence is sufficient to obscure hot spots, then specular walls may be used in some places in the luminaire. Specular walls can offer an advantage in terms of heat resistance and would be useful in areas close to the lamp. If multiple lamps are used in the luminaire, their position is not critical if a non-specular surface is used.

Clear Sky Simulation

Sky luminance varies smoothly from the horizon to the zenith, but the luminance level in each luminaire will be discrete. Efforts to shade the luminance level within the luminaire to accomplish a smooth variation will be extremely complex and have a low probability of success. In Figure 21, a space is shown (A) between the lower extremity of the luminaire and the dome wall. Using the integrating sphere concept, the flux will spread in all directions and the space (A) will permit a blending of luminance from one luminaire to the next. This is illustrated with a "ray" marked C in Figure 21. Where two luminaires along a constant latitude on the dome are at the same luminance, they each contribute and accept the same amount of flux. There is no discrete luminance change. Going from the horizon to the zenith, the luminaire at higher "latitude" will frequently have to be at a lower luminance than its neighbor. In this case, the more luminous fixture provides more flux to the gap (A) than it receives and can be expected to smooth over the discrete luminances. The distance (A) is a strong function of the number of luminaires used from the horizon to the zenith and the nature of the transmitting dome material. It is obvious that the blending of discrete luminances will be improved as the number of luminaires is increased or - put another way - by using more lower-wattage lamps versus fewer high wattage lamps.

The dome wall must function as a front projection screen for cloud and other special effects as well as a rear projection clear sky luminance diffuser. There is a direct trade-off between the dome's transmittance and the power requirements for clear sky and projected cloud effects. As the reflectance of the dome rises, the power required for internal projection decreases proportionately. The power required for clear sky simulation does not increase in the same proportion if the luminaires are operating as incomplete integrating spheres. The diffuse reflectivity of the wall tends to make the integrating sphere more complete and hence more luminant for a given lamp flux. This may be seen by determining the number of lamps required to provide a 2500 FL luminance versus the diffuse reflectivity of the dome. The estimate is based on the following equation which was physically verified by O. E. Miller and A. F. Sant of the Color Technology Division of Eastman Kodak Company.

$$N = \frac{F_o R_L^2}{A(1-\alpha R)} + \frac{F_o R_L}{(\Delta A)} \qquad (1)$$

N is the luminance of the wall in foot lamberts, F_o is the total flux entering the sphere, R_L is the absolute reflectance of the walls, A is the internal area of the complete sphere wall, and α is the fractional part of the complete sphere that remains. The second term represents the luminance of that part of the dome where the entering flux falls directly on the wall. In the luminaire, it is the unseen side of the diffuser or shield used to prevent the area being seen, directly by an observer. In determining the luminance apparent to an observer, the second term is not used. Consequently, α equals A minus the area of holes with the quantity divided by A. For a half sphere which approximates the luminaire, the value of α is 0.5. Experiment has shown that the above equation holds for shapes that depart markedly from a sphere.
As the "missing half" of the sphere is reduced by a diffusely reflecting sphere wall, the value of α will rise from 0.5 associated with a non reflecting wall. Allowing for a dome with diffuse reflectance of R_W and an absorption loss (a) of 10 percent in the wall, the equation will be:

$$\frac{N}{(1-a-R_W)} = \frac{F_o R_L^2}{A(1-\alpha R_L)} \qquad (2)$$

and $\alpha = 0.5(1+R_W)$ (3)

The luminaire must now be internally brighter by the quantity $1/(1-a-R_W)$. The reflectance R_L for the luminaire will be 0.94 or better if an acrylic white paint is overcoated with a barium sulfate sphere paint. This is a conservative value since reflectances approaching 0.98 can be achieved, with a less durable coating. Table 8 relates the number of luminaires required for the CSDF and the number of discrete luminaires required from the horizon to the zenith, versus dome wall reflectance (R_W).

It can be seen from the table that an increase in the reflectivity of the dome wall from 0.1 to 0.5 requires a 22 1/2 percent increase in the number of lamps and the external power requirement. However, the brightness of internal effects will be increased by a factor of 5. These internally generated luminance levels will be higher than the clear sky limits. Under some circumstances, the cloud luminances will approach 10,000 FL. Substantial consideration must be given to the internal projection situation when choosing a dome wall reflectance value.

Illumination for Cloud Effects

The luminance produced on the dome wall from an internal projector is strongly dependent on the diffuse reflectance of the dome, the gain of the internal surface of the dome, and the area illuminated. In view of the fact that the crew members are generally in the center of the dome, a brightness gain is possible if the cloud effect projector is reasonably close to the center and a high gain finish is applied to the inner surface.

The luminance in foot lamberts would be given by:

$$N_{FL} = E \times G \tag{4}$$

where the illumination is E and the screen gain is G. A perfect lambertian surface is defined as having a gain of 1. A diffusely reflecting surface with a reflectivity of 0.8 would have a gain of 0.8; consequently, both surface reflection and the controlled directionality of the reflection are contained in the gain term. The choice of surface treatment and selection of gain will be discussed later. Considering the output of a projector (L), the area (A) on the dome wall that is illuminated to luminance N_{FL} is

$$A \times N_{FL} = L \times G \tag{5}$$

The range of cloud luminances versus projected area that can be achieved is illustrated in Figure 22 based on a single 30 kw Xenon Short Arc lamp projector. The effective gain of the screen, which is the dome wall, is a driving parameter. If no special treatment is applied to the interior surface, the gain of 0.3 would be roughly comparable to the reflectivity of something less than 0.3, considered in Table 8. This comes about because a reflectivity of 0.3 applicable to clear sky luminance denotes a transmission of 0.6 which also applies to cloud illumination. When the cloud effects are projected on the wall, their brightness comes from two sources. The first is a 0.3 reflectivity from the wall. The second source comes from the 60 percent that is transmitted through the wall into the luminaire. The entire luminaire will "light up" with this additional flux and transmit some back to the CSDF. "Lighting Up" the luminaires in this manner is expected to produce unnatural cloud edges, especially when motion is simulated. Higher reflectivities will quickly reduce this effect and also reduce the burden on the internal cloud effect projectors.

Internal Reflection of Translucent Dome

The treatment considered for the internal surface of the translucent dome would resemble that used on a directional front projection screen. These screens have been constructed with peak gains as high as 200, but typical values for commercial screens are in the range of 0.7 to 3.5. If the dome wall was a perfect diffuser, its luminance pattern would be lambertian as illustrated in Figure 23(a). If directional characteristics are applied, the flux would be reflected in a preferred direction as shown in Figure 23(b).

The peak luminance gain is in the direction of the specular reflection. If the projector is normal to the screen, the peak gain will also be normal to the screen. The gain of a directional screen and the shape of the reflection pattern are a function of the surface texture, embossing utilized, and the specularity of the coating material.

Figure 24 illustrates the typical gain characteristics of standard (a) and lenticular screens (b) and (c). The higher gain of the "standard" screen surface cannot be controlled as readily as the lenticular. If there is parallax between the viewer

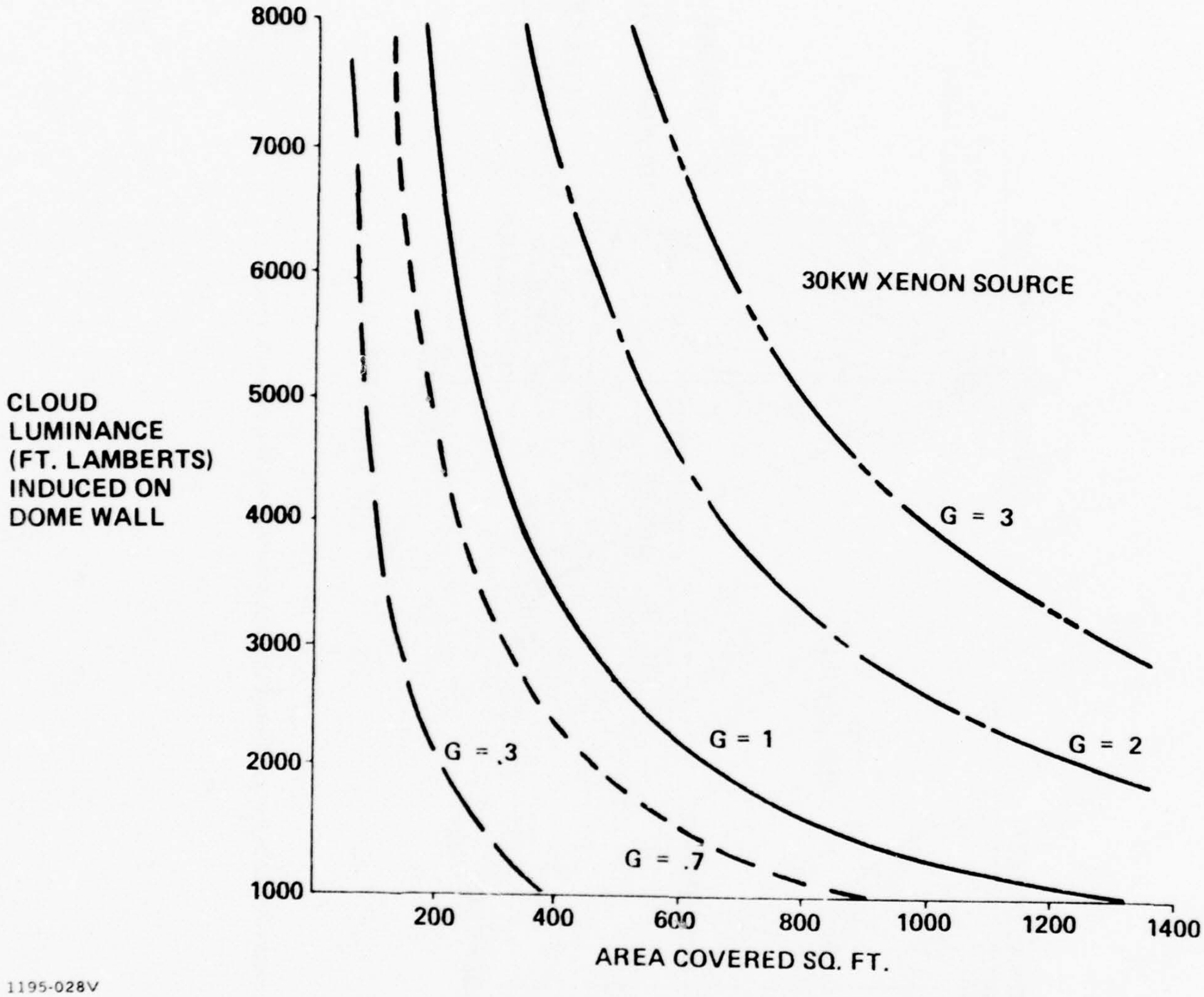

Figure 22. Induced Cloud Luminescence and Illuminated Area vs Screen Gain

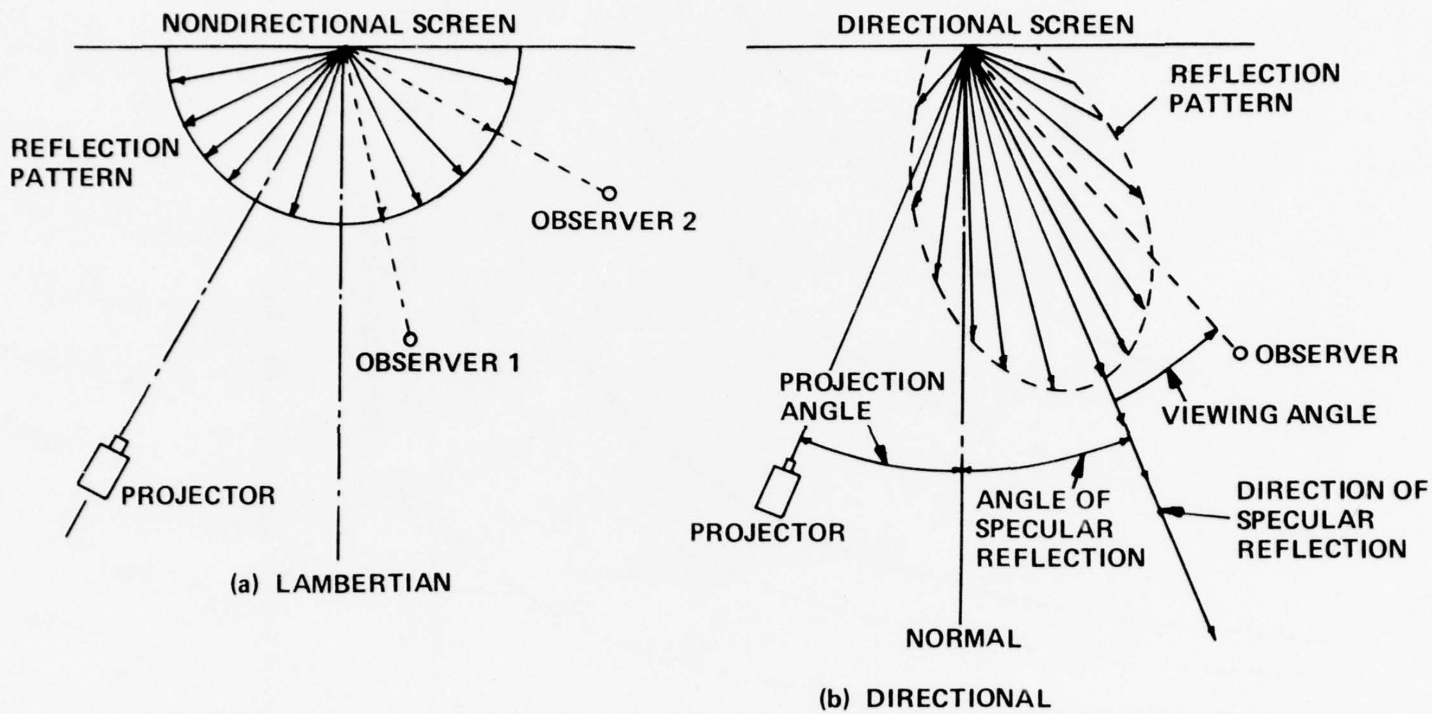

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Figure 23. Lobe Pattern From Lambertian Surface and Directional Screen

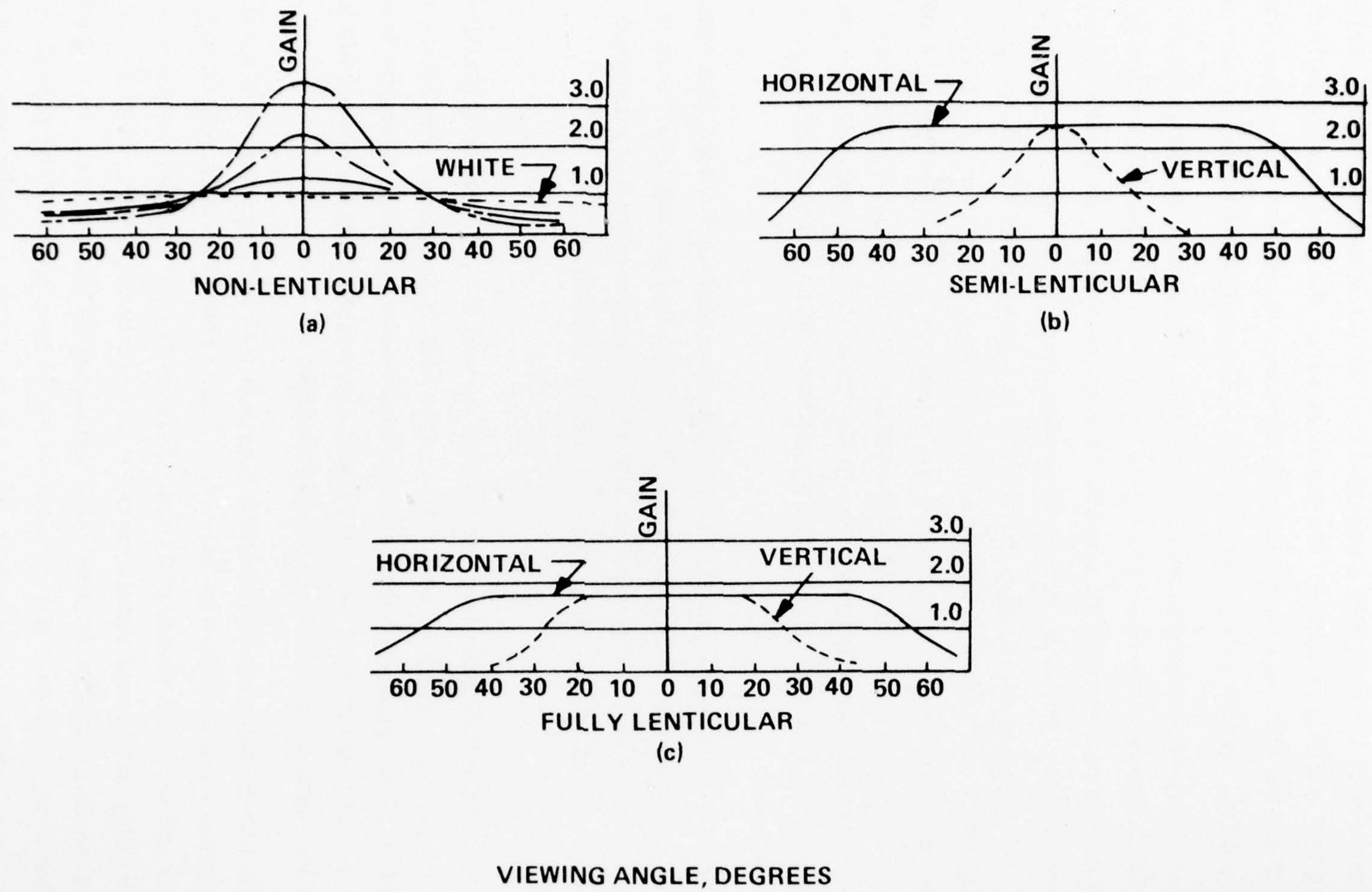

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Figure 24. Typical Gain Patterns of Standard and Lenticular Front Projection Screens

and the projector, the gain with a standard surface would not be at peak. This condition will exist in the CSDF. On the other hand, the zero viewing angle for a lenticular screen may be placed along the direction of specular reflection, illustrated in Figure 23(b). In this case, it is referred to as an oriented lenticular screen.

The choice of surface finishes is a detail design item. For purposes of feasibility, a conservative choice is a gain value of 1.8 for the fully lenticular surface. This value does not consider the translucent requirement for the dome. To serve both functions, the dome wall will be a combination of a rear and a front projection screen. Considering the physical requirements for the dome, it will probably become a development item. To be useful, the material must satisfactorily apportion the specular reflection from the interior surface and the back scatter from the diffusing elements. To allow for the overall transmittance of the wall, the gain is modified by the effective diffuse reflectivity, R_W in Equation (2). Consequently, the gain is established to be at least $1.8 \times R_W$ for comparison of the internal lighting provisions to the external.

For projecting an air-to-air target, the requirements for high gain internal reflection become even more important. The projection system must be servo-controlled at even higher rates than specified for the aircraft being simulated, making brute force projection apparatus more difficult to implement.

Sky Color

Because the HMI lamp has a continuous spectrum, color subtraction filters may be used to provide a range of colors from deep blue to deep red. The colors provided by a variety of commercial filters are illustrated on the C.I.E. chromaticity diagram, Figure 25. The spectrum of the basic HMI lamp would fall on the black body locus between the white of the overcast sky and sunlight.

The chromaticity coordinates and luminous transmittance values of a selected group of filters are identified in Table 9. This performance data applies to Kodak's scientific and technical series of filters. It is understood that these particular filters would probably not be sufficiently rugged to be used in the CSDF. They are cited here primarily to illustrate the relative color and luminous transmittance that can be jointly achieved. For the CSDF, the filters would have to absorb or reflect relatively high flux levels, and a detailed technical product search or development program might be necessary.

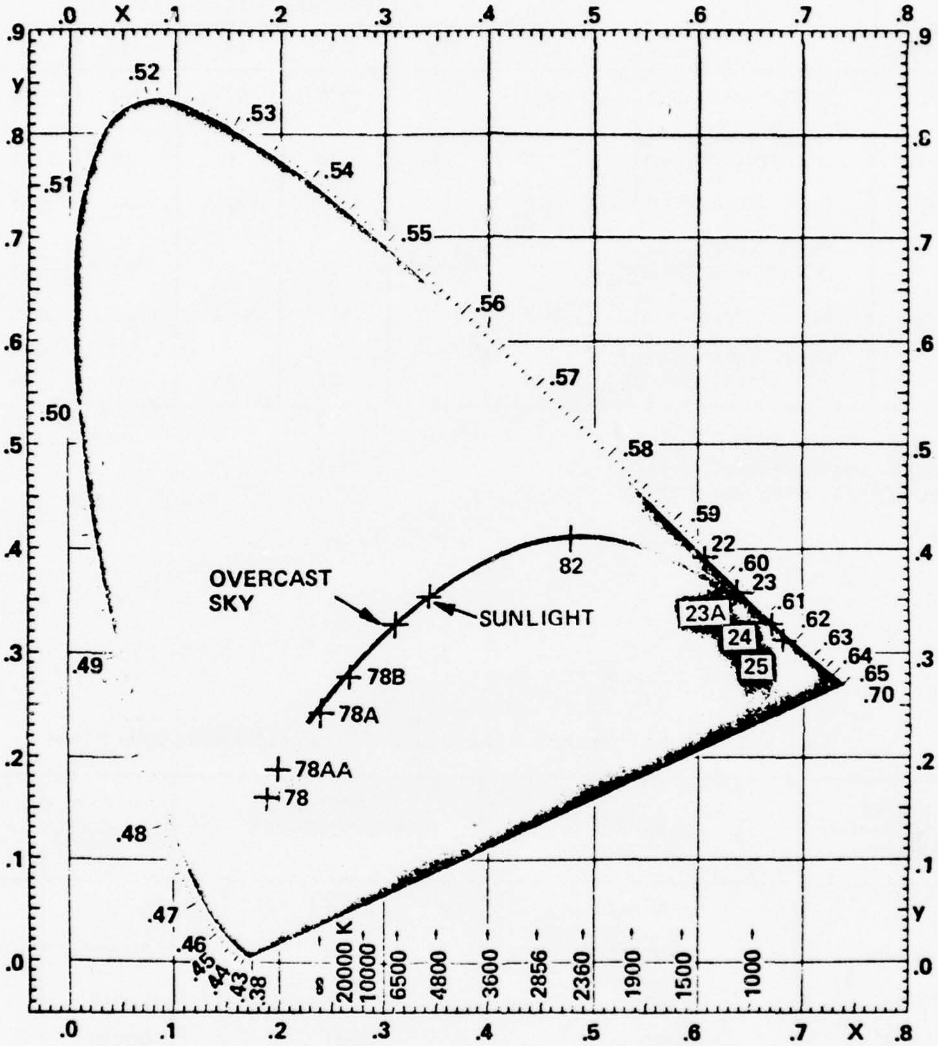

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Figure 25. C.I.E. Chromaticity Diagram

Table 8 Luminaire Requirements Versus Dome Wall Diffuse Reflectance to Produce 2500 FL Internal Luminance

LAMP* WATTAGE		DIFFUSE DOME WALL REFLECTANCE						
		0.1	0.2	0.3	0.4	0.5	0.6	0.7
2500	#LUMINAIRES REQ.	530	550	575	605	650	730	890
	NO. OF LUMINAIRES, HORIZON TO ZENITH	13	14	14	14	15	16	17
1200	NO. LUMINAIRES REQ.	1160	1200	1250	1320	1420	1590	1940
	NO. OF LUMINAIRES, HORIZON TO ZENITH	20	20	21	21	22	23	26
575	NO. LUMINAIRES REQ.	2610	2700	2810	2960	3190	3580	4350
	NO. OF LUMINAIRES, HORIZON TO ZENITH	30	30	31	32	33	35	39

*"HMI" METAL HALIDE LAMPS
DERATED TO 0.7 LUMINOUS OUTPUT

1195-32V

Table 9 Luminous Transmission of a Sample of Kodak Subtractive Color Filters

KODAK RECOGNITION NUMBER	COLOR	LUMINOUS TRANSMITTANCE*	CHROMATICITY COORDINATES	
			X	Y
78	DEEP BLUE	0.107	0.1911	0.1563
78AA	DEEP BLUE	0.158	0.2035	0.1857
78A	BLUE	0.316	0.2418	0.2406
78B	LIGHT BLUE	0.467	0.2670	0.2725
86	YELLOW	0.496	0.4773	0.4093
22	DEEP ORANGE	0.358	0.6030	0.3964
23A	LIGHT RED	0.250	0.6386	0.3610
24	RED	0.177	0.6675	0.3322
25	DEEP RED	0.140	0.6808	0.3190

*W/ DAYLIGHT C ILLUMINANT

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Table 9 suggests that sky luminance would decrease to essentially 16 percent of maximum white light luminance with a deep blue color (Filter 78AA). At an altitude of 45,000 feet, the zenith sky luminance is also 16 percent of its luminance from ground level (Figure 17). Data has not been found to establish the mean color at this altitude except that it can be profoundly blue. Lighter blues are available from the other filters at correspondingly greater luminous transmission.

For simulation of yellows, oranges and reds, there are many filters available. At this end of the spectrum, the luminous transmission is sufficiently high to permit a wide range of color effects and luminances. In view of the fact that real sky luminance levels are reduced proportionately with saturation of the apparent color, the use of subtractive color filters is suitable. Filters with luminous transmittance similar to those in Table 9 may be used without increasing the sky luminance requirement of 2500 foot lamberts.

Total Simulator Lighting Requirement

It was previously established that the choice of diffuse wall reflectivity would trade cloud effect power for clear sky simulation power. The trade is illustrated in Figure 26, using total lamp power as a parameter. The total power is shown to be a minimum for reflectivities from 0.3 to 0.50. The higher values are preferred because secondary illumination that could diffuse cloud edges will be substantially reduced. In addition, the number of high wattage Xenon lamps in the dome is reduced. The Xenon luminaires must be water cooled and they are expected to be basically more expensive as well.

Using a diffuse reflectivity of 0.5, the baseline illumination system is established as:

- Clear white and colored sky simulation
  - 1420 HMI lamps, 1200 watts each, to produce 2500 foot lamberts, individually controlled in intensity and color.
- Cloud effects
  - 26 Xenon lamps, 30 kw each, in projection luminaires to provide 10^4 foot lamberts on 2000 sq. ft. of dome (27% of the hemisphere), servo controlled in position, intensity and color.

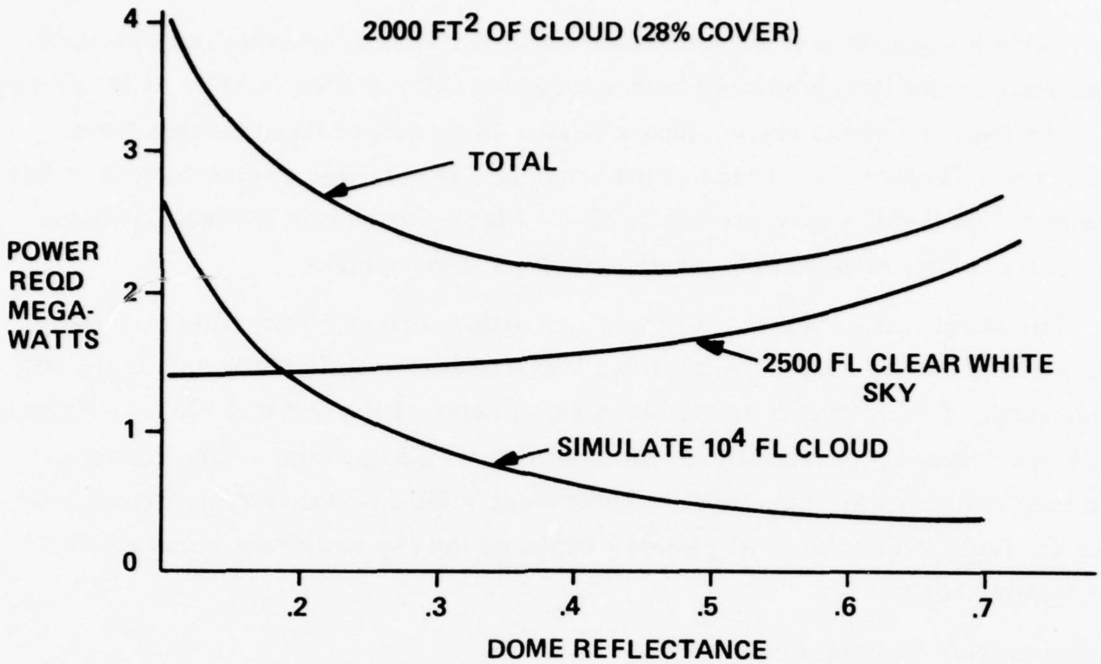

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Figure 26. Total Simulator Power Required for External Illumination System Versus Dome Reflectance

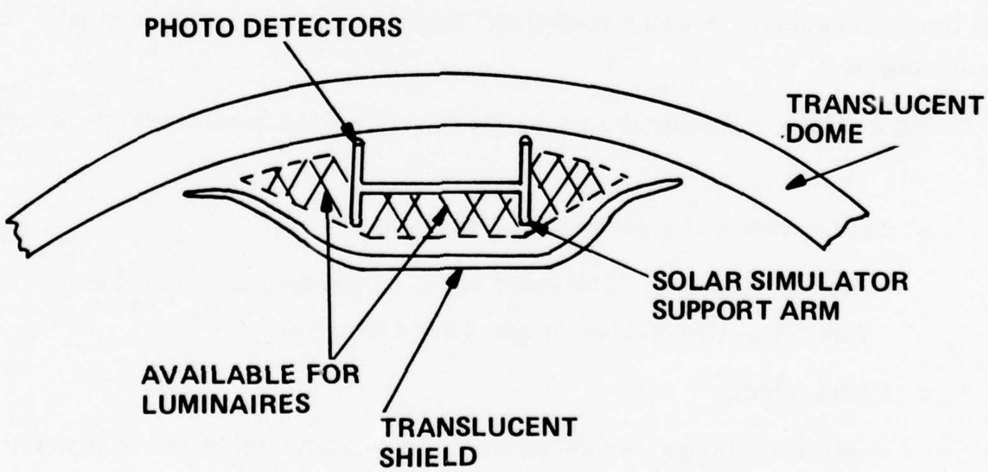

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Figure 27. Concealment of Solar Simulator Support Arm

Concealment of Solar Simulator Structure

The gimbals supporting the solar simulator will be silhouetted by the translucent dome and be highly visible unless local luminaires are employed in the structure. It is possible to use 200 watt HMI lamps in substantially smaller luminaires to backlight a translucent shield also carried on the gimbal arm. The luminance of this shield can be servo-controlled by sensing the luminance of the dome wall directly behind the gimbal structure. A sketch of a feasible concealment approach is illustrated in Figure 27. A section is shown through the arm; however, the same treatment is required around the solar simulator housings. The translucent cover would blend into the contour of the dome wall to minimize shadings and shadows. The technological considerations are similar to those associated with the basic external dome luminance approach.

INTERNAL ILLUMINATION SYSTEM

Illumination for the dome would be provided by luminaires located behind and below the cockpit and behind the movable terrain pan, as illustrated in Figure 8. Some luminaires would be used to provide clear sky illumination and the remainder could be grouped for simulations of clouds. The locations of the clear sky luminaires are such that direct wall illumination is not practical. The luminaires are close to the wall, and the flux is grazing on the wall near the horizon. The upper half of the sphere is generally illuminated by multiple reflections. Because of these factors, the wall must be as close to a lambertian surface as possible, and the gain will therefore be equal to the reflectivity.

The CSDF dome can be treated as an incomplete integrating sphere in the same manner as the luminaires for the external illumination system. In this case, however, the designer will have less control over the reflectance of the simulator components within the dome; thus, the performance of the dome as an integrating sphere will be compromised. The compromise would take the form of uncertainties in the value of α. Flux-absorbing surfaces, other than the dome wall, that are within the dome volume act as additional "holes" to lower the value of α. The solar simulator luminaires, for example, will increase the losses unless they have active illumination on their surfaces to compensate. Projections of cloud effects may also require luminaires and supporting structure to intrude above the dome's equator. The luminaires identified as D in

Figure 8 would have to be higher and tilted at a variety of angles to project to the horizon. This might not decrease α any further, but it could reduce the number of luminaires that can be accommodated.

Internal Clear Sky Simulation

Sky luminance accomplished with luminaires identified as A through E in Figure 8 is predicted by Equation (1). It is repeated here for convenience with appropriate modifications.

$$N = \frac{F_o R_W^2}{A(1-\alpha R_W)} + \frac{F_o R_W \ \mathrm{Cos}\ \theta}{(\Delta A)} \tag{6}$$

The reflectance subscript (W) identifies dome wall reflectance and the Cos θ term is added because the illumination is not normal to the wall. Since the flux from some internal luminaires can directly illuminate the walls, the second term may now become significant.

The largest lamps will be used to determine the relative feasibility. This does not imply that they are the final choice because experience suggests that a mix of large, medium, and even small luminaires may be preferable in terms of illumination and geometry.

The number of 30 kilowatt Xenon short arc lamps required to produce a luminance of 2500 FL is shown in Table 10 with wall reflectance and integrating sphere efficiency α as parameters. The table considers a lamp life derating factor of 0.7 and a 0.7 luminaire efficiency. It is applicable to luminaires A and E in Figure 8. For these luminaires, the Cos θ term is virtually zero, and the direct luminance term is of greatly reduced significance.

Figure 8 shows the locations of A and E luminaires. Table 10 is divided by a shaded line, and any combination of α and reflectivity to the left of the line will satisfy the luminance requirement. Wall reflectivity of 0.9 is considered reasonable for sustained operations. Allowing for uncertainties in the efficiency of the integrating sphere, an α value of 0.45 is selected. With this combination, a total of 41 lamps will be required. The luminance of 2500 FL will probably be exceeded slightly near the horizon in the vicinity of the lamps. This effect will not occur in the visual field of the sides of the cockpit with the luminaire distribution permitted in the dome. Additional

Table 10 Number of Xenon Short Arc Luminaires Required for Internal Dome Illumination to 2500 Foot Lamberts

LAMP	α	DOME REFLECTION COEFFICIENT						
		.97	.96	.95	.90	.85	.80	.75
30 KW XENON	0.6	25	26	27	32	38	46	55
	0.55	28	29	30	35	41	49	59
	0.50	31	32	33	38	45	53	62
	0.45	34	35	36	41	48	56	66

* DOME DIAMETER: 68 FT
* DERATED 70%
* LUMINAIRE EFF 0.7

α = FRACTION OF DOME INTERIOR THAT IS PRESENT

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Table 11 Minimum Clear Sky Luminance and Lamps Required for Cloud Simulation Versus Dome Reflectivity

DOME REFLECTIVITY	MINIMUM CLEAR SKY LUMINANCE FOOT LAMBERTS	NUMBER OF 30 KW XENON LAMPS REQUIRED
0.98	1940	26
0.94	1830	27
0.90	1720	28
0.85	1590	31
0.80	1470	33
0.75	1350	36

* 10^4 CLOUD LUMINANCE

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luminaires may be needed to the sides of the cockpit to provide a realistic horizon. These 41 lamps will produce a uniform sky. For cloud effects, direct projection is required from luminaries identified as B, C, or D.

Illumination for Cloud Effects

In a sphere, the flux that simulates the clouds at 10^4 FL will also illuminate the remainder of the dome. If 2000 square feet are illuminated to 10^4 FL, the remainder of the sky will have a minimum luminance that depends on the reflectivity of the dome. This can be a limitation on simulating a realistic blue sky with a group of white clouds. The induced sky luminance versus dome reflectance is illustrated in Table 11.

Reduced dome reflectivity results in moderately lower values of minimum clear sky luminances with a substantial increase in the number of lamps. Consequently, this minimum value must be accepted as characteristic of internally illuminated domes. This effect is substantially reduced in the externally illuminated dome because the reflection of the directly illuminated cloud is higher due to surface gain, and the directionality of the surface reduces the scatter from internal sources. This reduces the relative importance of the first term in the luminance equation for cloud projections in external illumination systems.

The 30 kw Xenon arc lamp was used for the analysis because it is a commercially available lamp whose spectrum is recognized as a good white. If smaller Xenon lamps are considered, the number required may be determined by ratioing their derated luminance value. For example, if 20 kw lamps are considered, the number of lamps would be increased by the factor 1.65. The luminaire could be reduced in size to compensate for the greater number of lamps. In addition, the individual Xenon lamp's emission can be reduced to approximately 50 percent without a spectral shift. For lower luminance effects such as sunrise, sunset, etc., the color correcting filter in the smaller luminaires would not be subjected to the higher flux densities of the 30 kw lamp.

The Xenon spectrum is rich in the near infrared (Figure 20) which will generally be transmitted by the luminaire into the dome enclosure. There will be a substantial thermal load imposed on the cockpit area by internal Xenon illumination as opposed to HMI lamps used externally. This load will be in addition to the equivalent solar constant delivered to the cockpit. A conceptual sketch of a Xenon luminaire is shown in Figure 28. The parabolic mirror intercepts virtually all radiated energy and directs it to the lens assembly. The water cooling provisions are not shown in the sketch.

Sky Color Simulation

In theory, sky color can be simulated with the same type of subtractive color filters described for the external illumination systems. There are a number of differences, however, that must be reported. The physical stress on filters used in this application is bound to be greater than with 1200 watt HMI lamps. If attempts are made to use relatively small Xenon lamps, the interior would have to accommodate more luminaires, and the increased surface area of the luminaires would create more flux trapping regions. This would lead to higher wattage requirements for sky illumination.

It was determined that 41 luminaires arranged about the periphery of the dome would be adequate to provide the clear sky luminance of 2500 foot lamberts. This is in white light and may be brighter at the horizon than the zenith. If these luminaires are filtered, the brightest blue may appear at the horizon. The more realistic shading of a generally white or light blue sky at the horizon to a deeper blue at the zenith will be very difficult, if not impossible, to obtain. In addition, the general background sky luminance induced by cloud projection is white (Table 11). Mixing this white flux with filtered flux will not give the same color saturation. On the C.I.E. chromaticity diagram, the color will shift along a straight line connecting the filtered and white light in proportion to the relative illumination in each color.

If color is to be simulated, there is a distinct possibility that the luminaires should project directly to the dome wall. This would relegate the volume around the periphery of the dome for secondary lighting effects and require all luminaires to be in the regions marked B, C, and D in Figure 8 for realistic simulation of sky color. In this case, the number of 30 kw luminaires required is 23 for sky illumination and another 28 for cloud effects.

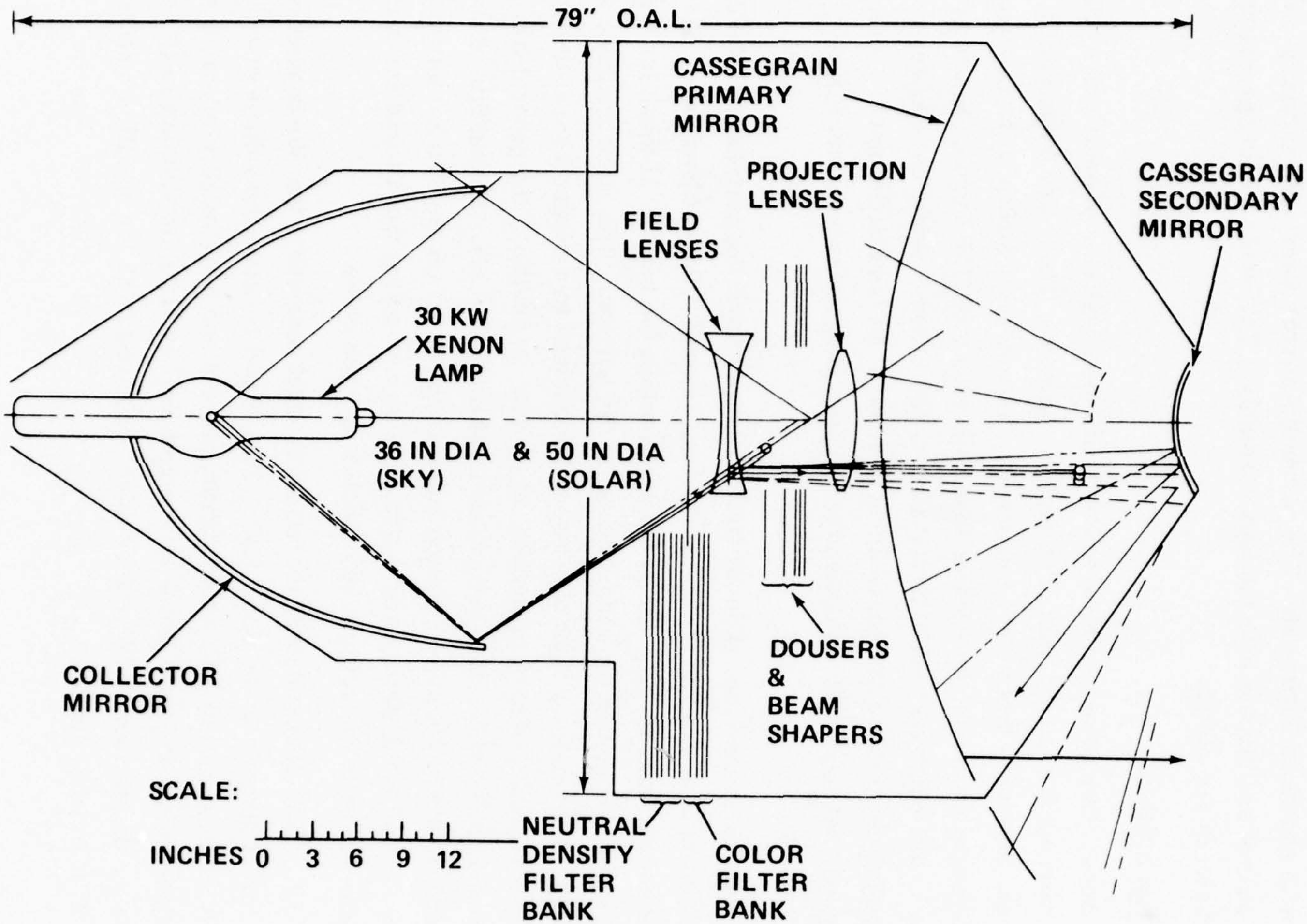

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Figure 28. Solar & Sky Simulator Luminaire Design

If this is done, then movement of the terrain pan imposes another lighting problem. In order to illuminate the sky without inappropriately illuminating the pan at the horizon line, the flux must be carefully directed to the wall. When the pan attitude changes, the sky illumination must be servo controlled to avoid direct illumination of the pan. Putting the sky luminaires near the center of the sphere and projecting directly on the dome decreases the total number of luminaires required. It also makes a more realistic shading of the sky luminance and color from horizon to zenith possible. It does require position as well as intensity and color control on these luminaires. The 28 luminaires designated for cloud effects must have position and intensity controls. The number of luminaires is based on providing 10^4 foot candles over 2000 square feet of surface. This group of 28 luminaires can be reduced if less cloud cover is desired and/or if less than 10^4 FL is to be achieved.

Total Simulation Lighting Requirement

The total major lighting requirements for an internally illuminated system must be summarized separately for the alternatives that were previously identified:

- For Sky Illumination With Peripheral Luminaires
  - 41 Xenon short arc luminaires, 30 kilowatts each, controlled in intensity and color for clear sky simulation.
  - 28 Xenon short arc luminaires, 30 kilowatts each, servo controlled in position, color and intensity, for cloud effect simulation.

The sky color can be a major design risk in this approach.

- For Sky Illumination With Centrally Located Luminaires
  - 23 Xenon short arc luminaires, 30 kilowatts each, servo controlled in position, color and intensity for clear sky simulation.
  - 28 Xenon short arc luminaires, 30 kilowatts each, servo controlled in position, color and intensity, for cloud simulation.

The physical positioning and control of the 21 additional luminaires close to the cockpit is a major design consideration.

PREFERRED SKY SIMULATION

The general performance characteristics of the externally illuminated dome and the two versions of the internally illuminated domes are summarized in Table 12. All three versions can simulate the required sky luminance. The three approaches are substantially different in terms of the quality of simulation and the implementation. In making the feasibility estimates, a projected cloud cover of 2000 square feet was used with no justification other than the fact that 27 percent coverage seemed to be a reasonable upper requirement. The effort to implement this requirement is substantially the same for any of the lighting concepts, consequently it should be cancelled out of the comparison. This is true if the comparison is confined to the cloud simulating luminaires. However, in the internally illuminated dome where the clear sky luminaires are projecting directly on the dome from positions near the center of the dome, the two sets of luminaires will compete for position (area D in Figure 8). A virtually insurmountable mechanical design problem is created. If fewer luminaires are used because of space limitations it is equivalent to reducing the number of cloud simulating luminaires from 27% coverage to something less. This reduction is applicable to all three approaches.

When the simulation quality is considered, only the externally illuminated dome can produce reasonable control of luminance color and contrast. It allows multi-color sky and luminious and color gradations in the intended locations. On the basis of performance the externally illuminated dome is the preferred approach. It requires more electrical power than the other approaches, but the difference is small and the improvements in simulation capability is significant. A comparison of the total illuminating power for the three systems is made in Table 13. In each case the electrical load is constant. The time constant associated with turning the lamps on requires all to be lit at the same time even though the horizon/terrain pan is obscuring the wall being illuminated as illustrated in Figure 37. An additional half megawatt of power will be required for the translucent dome but the performance advantages that accrue make it worthwhile. Consequently, the externally illuminated translucent dome is the preferred implementation.

Table 12 Comparative Performance CSDFS Illumination Systems

CHARACTERISTIC	EXTERNALLY ILLUMINATED, TRANSLUCENT DOME	INTERNALLY ILLUMINATED, OPAQUE DOME SKY LUMINAIRES LOCATED PERIPHERALLY	INTERNALLY ILLUMINATED, OPAQUE DOME, SKY LUMINAIRES CENTRALLY LOCATED
2.5×10^3 TO 10^4 FL WHITE SKY LUMINANCE	ACHIEVABLE, ALL LAMPS BURN ALL THE TIME, INTENSITY MECHANICALLY CONTROLLED	ACHIEVABLE, ALL LAMPS BURN ALL THE TIME, INTENSITY MECHANICALLY CONTROLLED	ACHIEVABLE, ALL LAMPS BURN ALL THE TIME, INTENSITY MECHANICALLY CONTROLLED
SKY COLOR BLUES	READILY ACHIEVABLE SHADES LUMINANCE AND COLOR FROM HORIZON TO ZENITH. SUBTRACTIVE COLOR FILTERS, LOW FILTER THERMAL STRESS	EXTREMELY DIFFICULT TO SHADE LUMINANCE AND COLOR CORRECTLY FROM HORIZON TO ZENITH. SUBTRACTIVE COLOR FILTERS, HIGH THERMAL STRESS	DIFFICULT TO SHADE LUMINANCE AND COLOR CORRECTLY FROM HORIZON TO ZENITH. SUBTRACTIVE COLOR FILTERS, HIGH THERMAL STRESS
YELLOWS - REDS	READILY ACHIEVABLE, SAME AS ABOVE	ACHIEVABLE, SAME AS ABOVE	ACHIEVABLE, SAME AS ABOVE
COLOR QUALITY	SATURATED COLORS ACHIEVABLE	UNSATURATED COLORS WILL RESULT	UNSATURATED COLORS WILL RESULT
COLOR SEPARATION	BLUE SKY WITH RED HORIZON (SUNRISE) READILY ACHIEVABLE, WHITE CLOUD CAN ALSO BE SIMULATED	NOT ACHIEVABLE, ALL COLORS WILL BE BLENDED TO PRODUCE NEW HUES	NOT ACHIEVABLE, ALL COLORS WILL BE BLENDED TO PRODUCE NEW HUES
APPARENT ALTITUDE	SKY APPEARANCE CAN REALISTICALLY SIMULATE ALTITUDE	NOT EXPECTED TO BE POSSIBLE	MAY BE SIMULATED TO SOME DEGREE
CLOUD SIMULATION TO 10^4 FL	ACHIEVABLE WITH MINIMAL LOSS OF COLOR CONTRAST AND CHANGE IN SKY LUMINANCE	ACHIEVABLE, MINIMUM SKY LUMINANCE AND HUE VARIES WITH EXTENT OF CLOUD PROJECTION	ACHIEVABLE, MINIMUM SKY LUMINANCE AND HUE VARIES WITH EXTENT OF CLOUD PROJECTION

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Table 13 Major Illuminating Power Requirements

EFFECT	EXTERNALLY ILLUMINATED DOME		INTERNALLY ILLUMINATED DOME			
			PERIPHERAL LUMINAIRES		CENTERED LUMINAIRES	
	NO. OF 1200 WATT LAMPS	WATTS $\times 10^6$	NO. OF 30 KW LAMPS	WATTS $\times 10^6$	NO. OF 30 KW LAMPS	WATTS $\times 10^6$
2500 FL SKY ILL.	1420 HMI	1.70	41 XENON	1.23	23 XENON	0.69
CLOUD TO 10^4 FL	26 XENON	0.78	28 XENON	0.84	28 XENON	0.84
	TOTAL	2.48	TOTAL	2.07	TOTAL	1.53

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SECTION IV
SOLAR SIMULATION

Solar simulators have been used extensively for product testing, accelerated aging of materials, spacecraft testing, etc. The design trade-offs are related to the size and brightness of the source, the intensity desired, and the size of the test area. In this case, the cockpit or cabin geometry requires the minimum size area of solar beam coverage to be 44 x 36 inches.

It is axiomatic that the simulated sunlight should have the correct intensity and spectral content; it should flood the essential parts of the cockpit and not spill out into the remainder of the simulator.

The basic cockpit dimensions are determined by MIL-STD-1333 which defines the reach and panel visibility envelopes. A general cockpit arrangement is illustrated in Figures 29 and 30. Generally the forward cockpit must have illumination for at least 44 inches fore and aft to illuminate the wind screen and the Heads Up Display and 36 inches side to side. A tandem cockpit is illustrated in Figure 31. The tandem rear cockpit would generally require illumination over a 36 x 36 inch area. The 36 inch wide beam would be applicable for a side by side or tandem aircraft. The canopy is 36 inches wide and the illuminated region extends over a 9-foot length.

SOLAR SIMULATOR ALTERNATIVES

Solar simulation per se does not present any special technological problems. Simulators can be designed using a 30kw Xenon short arc source that provide a local solar constant with very satisfactory spectral content. The solar constant can be delivered to the test area in a range of collimation angles. The closer the apparent size of the simulated disc is to the sun's angular subtense the larger the collimation optics required. The problems associated with solar simulation arise from its incorporation in the CSDF simulator.

In general solar simulation can be introduced into the CSDF dome by a number of schemes, two of which will be illustrated. They involve the direct gimballing of the simulators within the dome and the use of gimballed mirrors in the dome to service fixed simulators. The first alternative is illustrated in Figure 32. The solar simulators are rotated about a point in the cockpit on a track gimballed about the yaw axis. While all solar positions can be reproduced by this arrangement making it a feasible

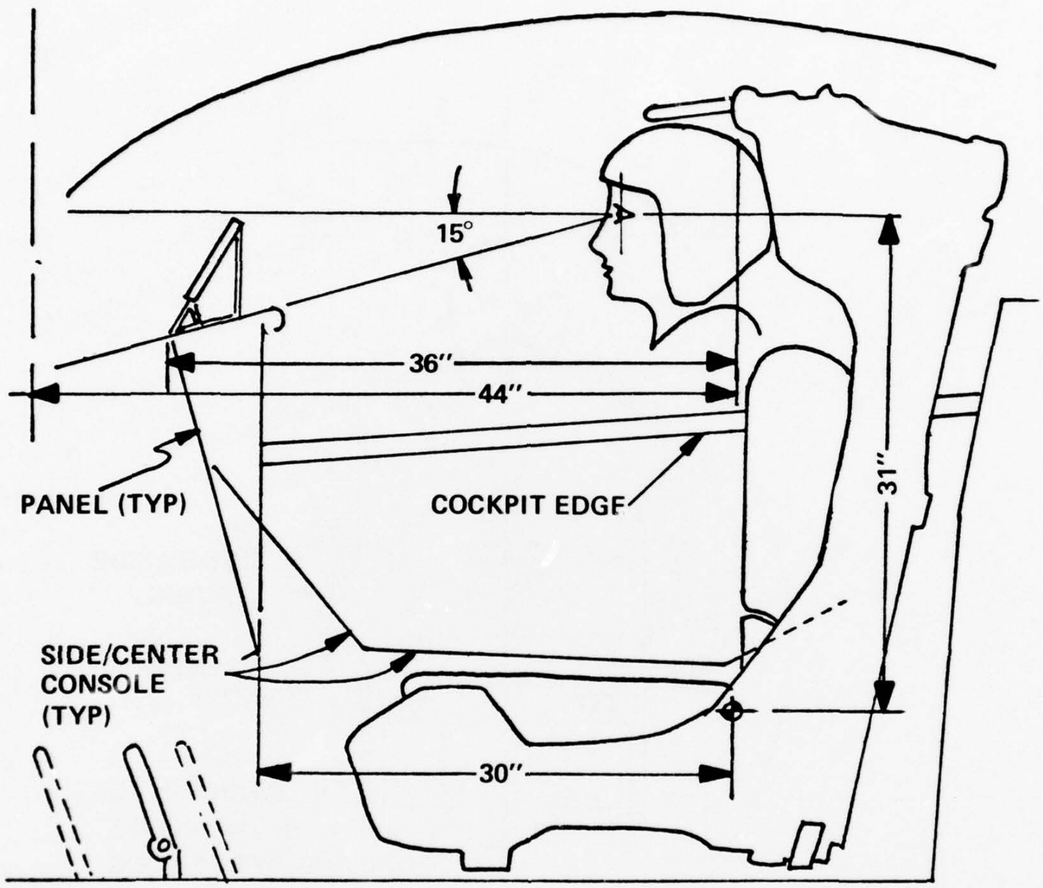

Figure 29 Typical Cockpit Arrangement For Aircraft Crewman (Side View)

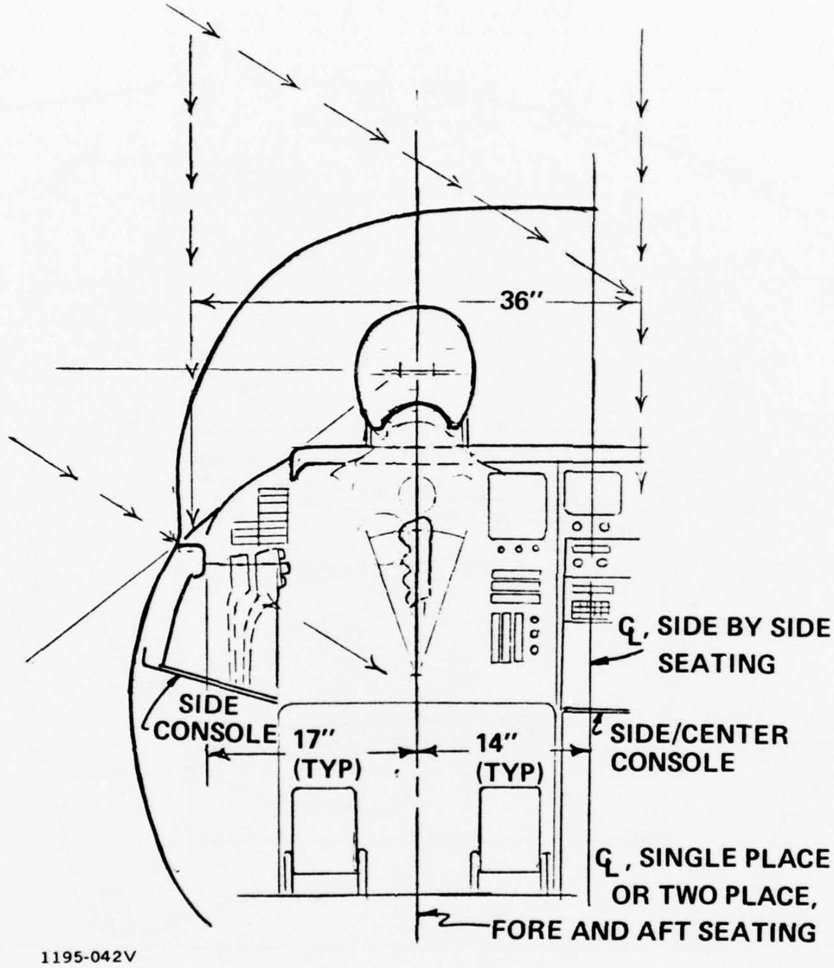

Figure 30. Typical Cockpit Arrangement (Rear View)

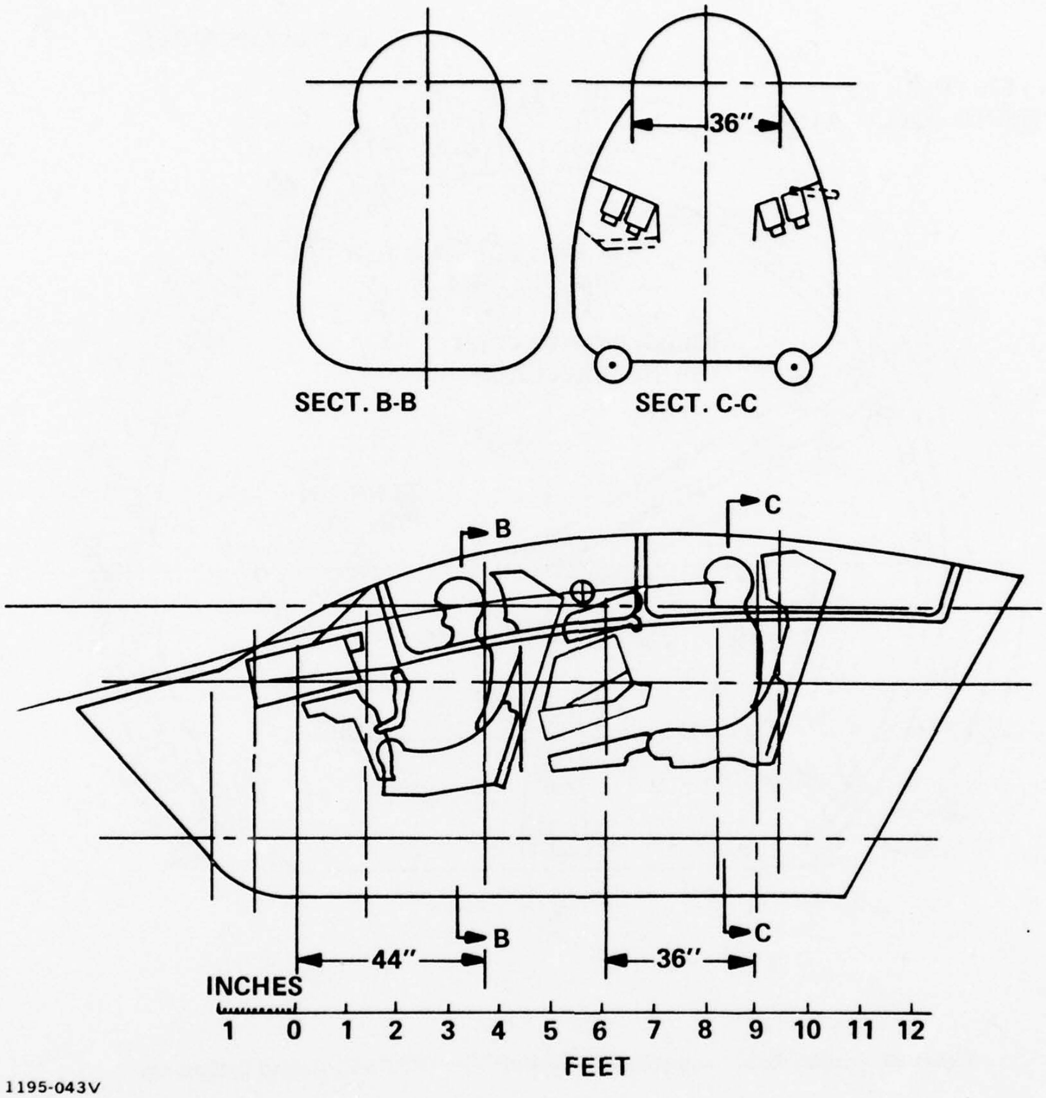

Figure 31. Dimensions of a Tandem Cockpit

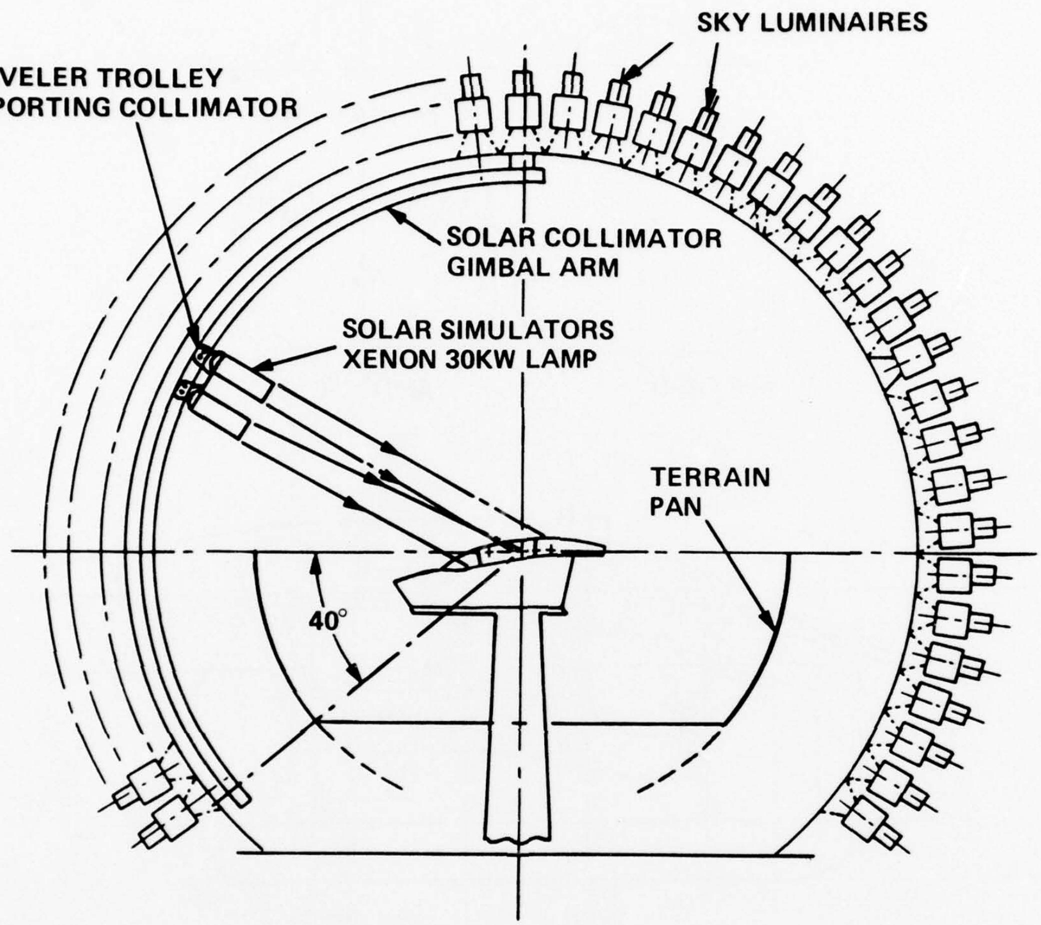

Figure 32. Possible Solar Simulation Configuration for CSFDS Gimballed Collimators

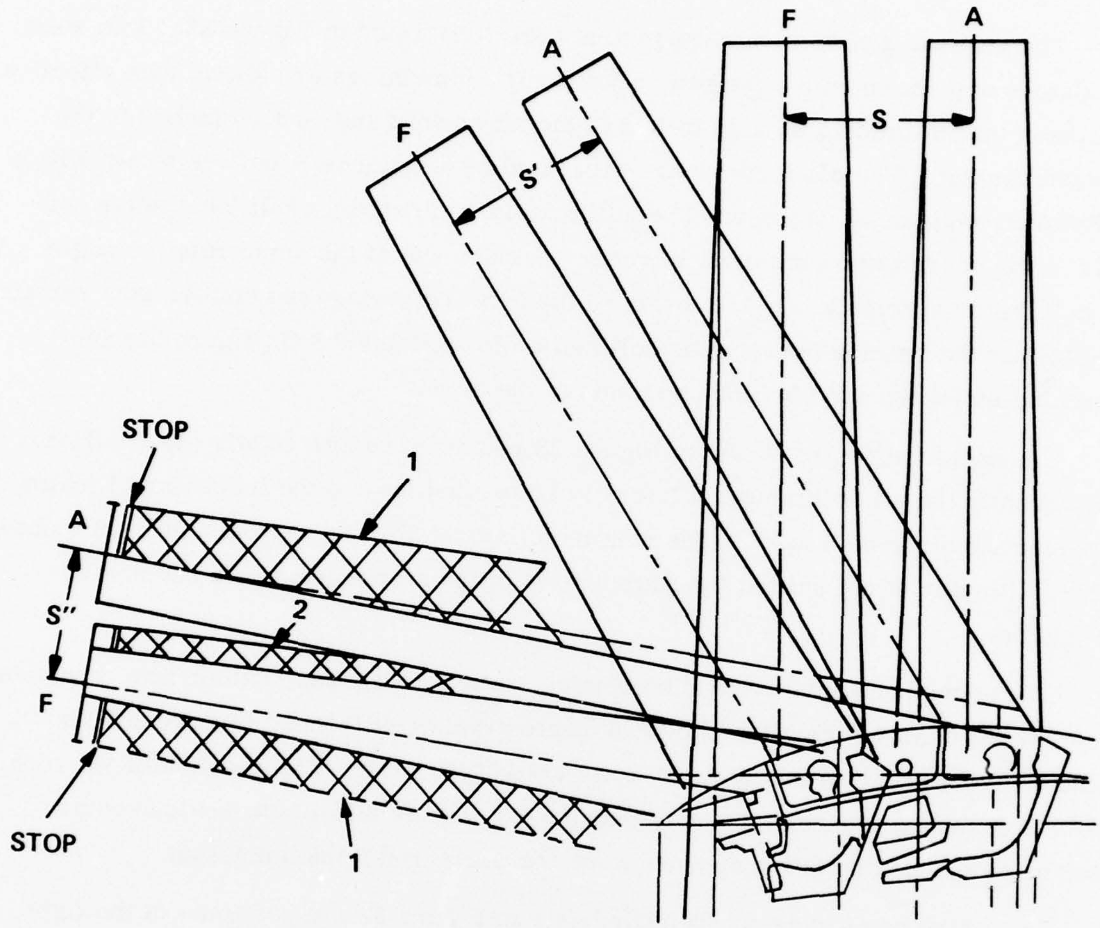

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Figure 33. Solar Simulator Geometry

approach it is understood that the choice of gimbal axis may not be optimum. The collimators must be moved in the region between the movable terrain pan and the wall of the dome to permit the "sun" to rise and set.

The general illumination requirements are illustrated in Figure 33. Two solar simulators are shown with a tandem cockpit. The simulators are shown with effective apertures that illuminate 36 x 36 inches in the aft cockpit and 44 x 36 inches in the forward cockpit. The collimators are separated by a distance S and are shown with a collimation angle of ± 2 degrees. The collimators can deliver a full local solar constant to the cockpit and each crew member sees one sun at the same relative angle. As the collimator assembly is rotated toward the forward horizon the optical axes remain parallel but the spacing between the collimation is reduced $S'' < S$ (Figure 33) and vignetting stops are used to block portions of the beam.

The collimators are shown in Figure 33 rotated about the pilot's eye position. Consequently the aft collimator is laterally translated toward the forward collimator to reduce the distance S to S". The maximum lateral shift is approximately 20 inches. If the collimator is not shifted the illumination of the aft cockpit would become unacceptable.

The second collimator could be rotated about 4.5 degrees, rather than translated, to center the beam of the aft cockpit. A corresponding difference in apparent sun positions from the front and rear cockpits would then exist. Examination of the requirements to simulate "sunset" suggests that the 4.5 degree difference would become objectionable and translation appears to be the preferred implementation.

The cross hatched areas identified as 1 in Figure 33 are positions of the light beam that no longer fall into the cockpit and are extraneous light sources in the simulator. A mechanical stop must be provided in each collimator which is programmed to sharply vignette the beam as a function of simulator position relative to the cockpit. The stop system must also vignette the beam to prevent a crew member from seeing two suns. This is illustrated by cross hatches (area 2) in the figure. The stop prevents the aft crew member from seeing a multiple source. Similar vignetting must be provided for sun rotation to the side to limit the sun beam to the cockpit.

For two abreast cockpits the geometry and vignetting requirements are generally rotated 90 degrees. One collimator is required per crew station. Analysis of this configuration established the following:

- The sun can be simulated to the required spectral accuracy and confined to the cockpit area

- The radius of the dome depends on the collimation angle provided in the solar collimator. It is the sum of the distance from the dome center to the terrain pan plus the clearance volume for the collimator, the size of the collimator depending in turn on the collimation angle provided.
- The path of "sun light" in the dome is realistic and all sun angles can be simulated
- The power and cooling lines required by the solar simulators must be accommodated on the gimbal arm and across the gimbal
- "Motion" of the simulator requires rapid acceleration of the solar support structure whose moment of inertia is inherently large
- The body of the simulator and the supporting gimbal structure will be in silhouette against the sky requiring fill-in lighting on the visible portion of the structure to blend with the "sky" behind it.

The second alternative is illustrated in Figure 34. In this configuration the lamp housings and their optics are stationary and sun motion is induced with gimballed mirrors. The lamp housings and their optics can be located at position A or B. If the lamp housings are mounted at location A and the first mirror is mounted at location B, this mirror could have power and be part of the collimation system. If the lamps are mounted at B, the throw between the collimators and the cockpit is less for the case where the lamps are mounted at A. However, if the large mirror at B is configured as a collimator, the throw between the collimators and the cockpit would be equal to the case where the lamps are mounted at B. This is an important consideration that reduces the allowable collimation angle and increases the size of the collimators. This may be evaluated by considering the geometry of collimators illustrated in Figure 35. The collimation angle (θ) and the exit pupil (D) determine the region A within which the simulated sunlight is constant. As the distance (L) from the collimator to the point of interest increases, the diameter (d) of the area illuminated with maximum output decreases. If the collimator is producing a solar constant over a diameter (D) it will illuminate a smaller diameter (d) at a distance L from the collimator. Beyond point B the irradiation falls off by inverse square of the distance L. The relative effect of this geometry is shown in Figure 36 for a range of collimation angles. Gimballed collimators are represented by the solid curves, and gimballed mirrors systems (with

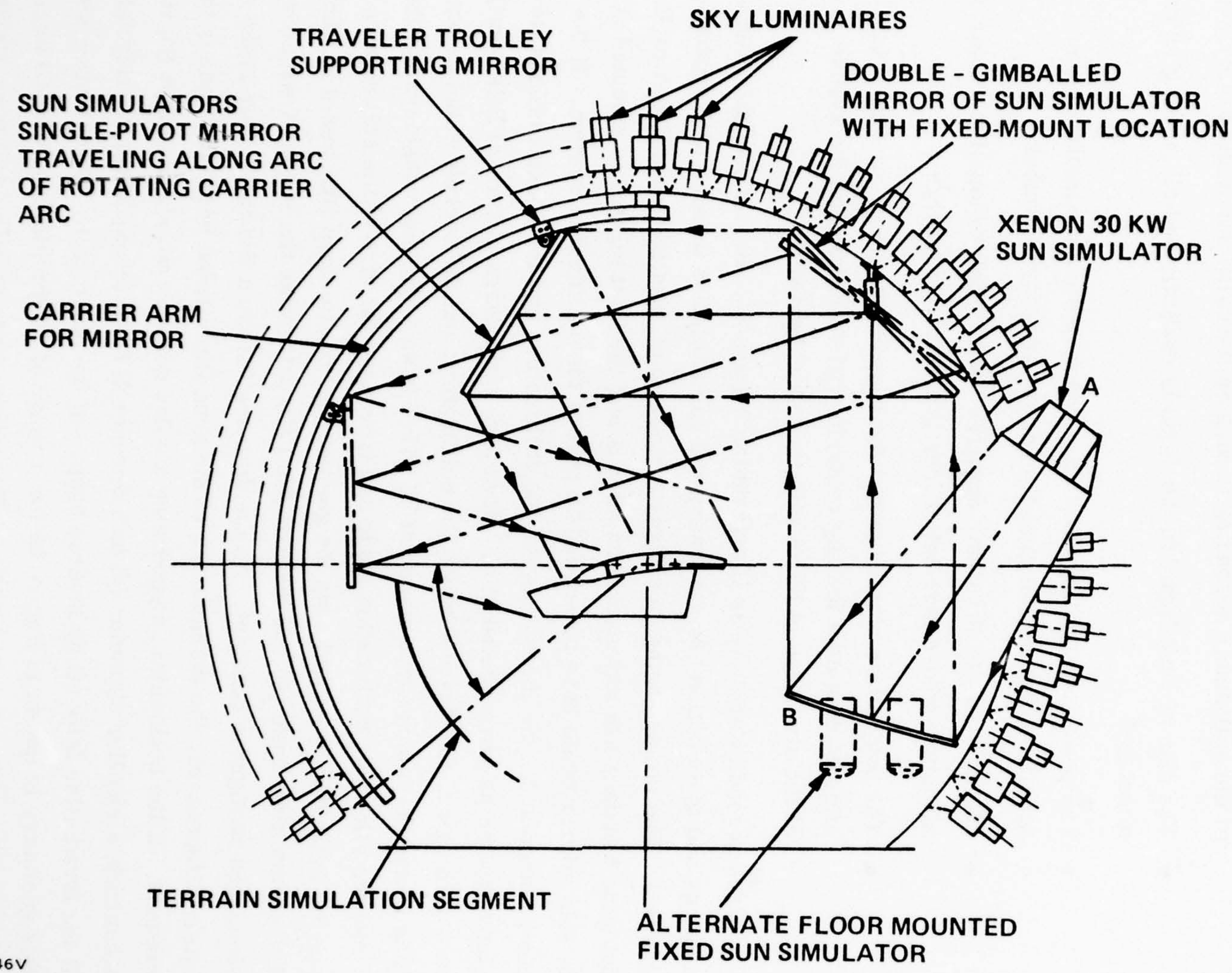

Figure 34. Solar Simulation – Gimballed Mirror Approach

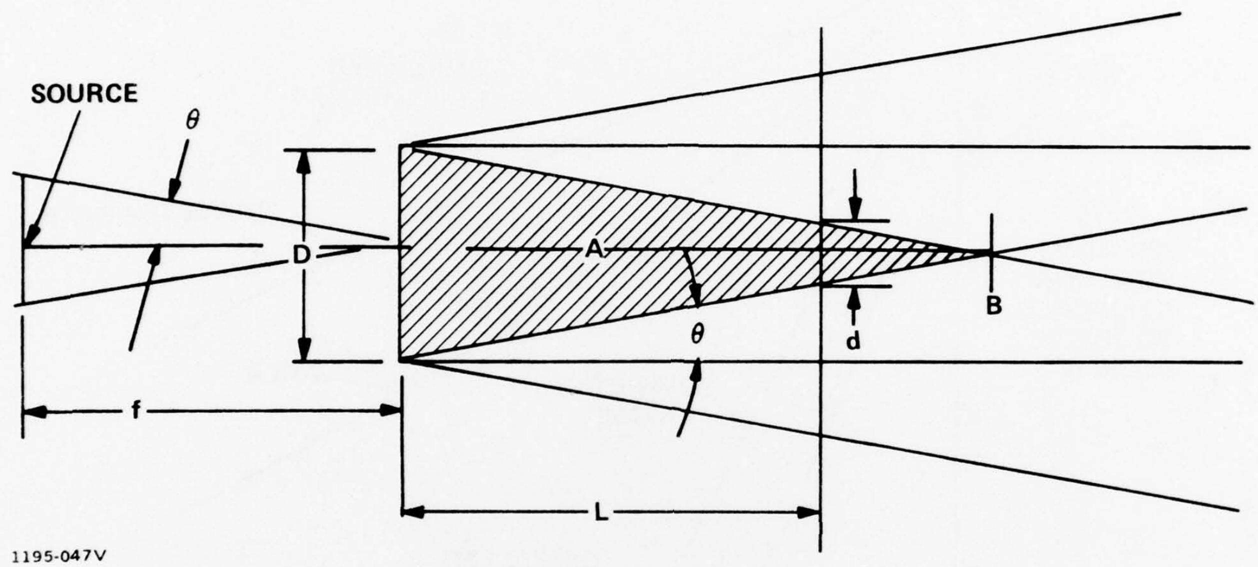

Figure 35. Collimator Geometry

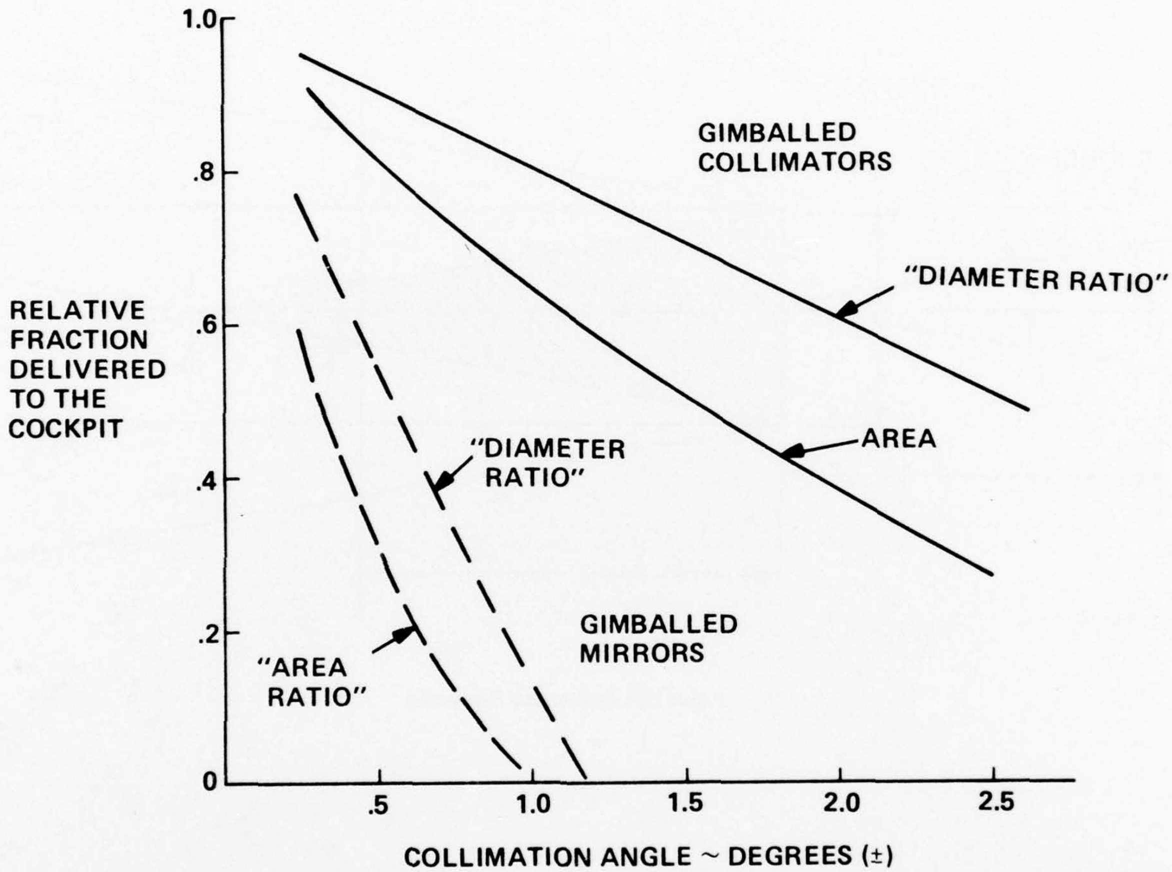

Figure 36. Ratio of the Diameter and Area of Fresnel Zone to the Diameter and Area of the Exit Pupil for Direct Gimballed Collimators vs Collimators with Gimballed Mirrors

the sources inside the dome) are shown by the broken curves. For any given collimation angle the ratio of the uniformly illuminated diameter or area, at the cockpit, to the diameter or area of the collimator's exit pupil is expressed as a fraction. The collimator's exit pupil must be larger than the illuminated cockpit geometry by the reciprocal of the ratio. Effectively for all collimation angles greater than 1.0 degree the cockpit is in the inverse square region for gimballed mirrors. Multiple sources will be required to achieve a solar constant if they are placed at point B in Figure 34. If the sources are placed at point A, the first mirror at B would provide a collimated "sun". Its diameter would be approximately 15 feet to provide a 0.5 degree sun. Individual gimballed collimators would have a diameter of approximately 4 feet to provide the same quality simulation.

Another aspect of using gimballed mirrors is the multiple paths the "sunlight" takes in the dome. Other simulated effects such as clouds will be unnatural if these reach any positions occupied by the solar illumination beams.

Analysis of this alternative established the following:

- The mirrors must be very large to avoid the appearance of multiple "suns"
- The movable mirrors would have substantially less mass than other approaches with substantial reductions in the moment of inertia
- The simulated sunlight cannot be steered through the full 2π steradians of the upper hemisphere. Discontinuities will exist "overhead" and sun can not be simulated at low elevations from behind the cockpit
- The mirrors blank out parts of the sky simulation and create erroneous illumination patterns by reflecting extraneous regions of the CSDF to the crewmen
- There are four shafts of light which will distort the pilot's sensation of ambient illumination and will reduce his ability to view the sky and terrain simulation in clear-atmosphere operation. This effect becomes totally objectionable if fog, haze, and other similar ambient conditions are simulated by injecting "smoke" in the region between the cockpit and the inner dome surface.

Vignetting of Sky

The solar simulator structure will vignette the sky behind it when the structure is inside the translucent dome. For a directly gimballed collimator the telescope structure and the supporting track and gimbal will block different regions of the sky. For a gimballed mirror system the mirrors and their gimbal structure will do the same. In addition the mirrors can make extraneous regions of the dome interior visible to the crew.

The non-reflecting components of the solar simulators to the pilots can be made less visible by illuminating the structure to the same brightness as the local sky it is vignetting. This can be illustrated for the translucent dome. The sky brightness would be sensed by photo cells and the translucent casing on the structure would be back-lighted to be as luminous as the sky. (Refer to Figure 27). Where specific sky color was being simulated the implementation would have to be repeated for the structure's back lighting system. A closed loop system, which senses the sky luminance behind the structure and the luminance of the face of the structure, can perform the task. It is possible that an open loop system could be satisfactory which just responds to the sky luminance behind the structure and the color being simulated. Fill-in lighting is necessary with an externally illuminated dome but not for internal illumination. In either case the solution is expected to be more satisfactory for external illumination translucent dome than for internal opaque dome. This is based on the fact that an internal illumination system, with an opaque dome, will generally have shadows cast by the structure plus luminance variations caused by direct illumination on lower portions of the support structure. Fill in lighting will be complicated by this variation which will also be strongly variable with relative sun position. In the translucent dome there will be less problem with shadows, if in fact any shadows will be present. The fill-in lighting task will be more straightforward.

FEASIBLE SOLAR SIMULATION

As a result of the tradeoff studies the directly gimballed simulator was chosen as the best approach. The directly gimballed collimator offers the possibility of realistic simulations and the gimballed mirror system does not. Furthermore the disadvantages of this approach in terms of moment of inertia and the logistics of supplying power and cooling to the moving collimators are outweighed by the disadvantages associated with the gimballed mirror approach. The general tradeoffs are listed in Table 14. It must be recognized that both systems can be improved by detail

Table 14 Comparison of Solar Simulation Alternatives

PARAMETER	DIRECT GIMBALLED COLLIMATOR	GIMBALLED MIRROR, FIXED COLLIMATOR
SPECTRAL CONTENT	SATISFACTORY	SATISFACTORY
COLLIMATION ANGLE	SATISFACTORY DESIGN FREEDOM, SINGLE "SUN" SEEN BY CREW	UNSATISFACTORY DESIGN FREEDOM, MULTIPLE SOURCES REQUIRED
SOLAR INTENSITY	SOLAR CONSTANT POSSIBLE WITH ONE "SUN" VISIBLE TO CREW, CONSTANT WITH POSI-TION	SOLAR CONSTANT POSSIBLE WITH MULTIPLE SOURCES
FLUX CONFINEMENT TO COCKPIT	POSSIBLE WITH COMPUTER CONTROLLED MECHANICAL STOPS IN COLLIMATORS	POSSIBLE WITH COMPUTER CON-TROLLED MECHANICAL STOPS ON MIRROR AND COLLIMATOR
SIMULATION REALISM	REALISTIC IN APPEARANCE AND DIRECTION	MULTIPLE (4) BEAMS, DIRECTIONS; INCOMPATIBLE WITH CLOUD, FOG SIMULATION –
COVERAGE	ALL SUN ANGLES CAN BE SIMULATED	NOT POSSIBLE TO SIMULATE SUN AT ALL ANGLES
POWER & COOLING MOTION	DESIGN PROBLEM LARGE MOMENT OF INERTIA	NO DESIGN PROBLEM MODERATE MOMENT OF INERTIA
FILL-IN LIGHTING	PROBABLY SATISFACTORY	POSSIBLY SATISFACTORY

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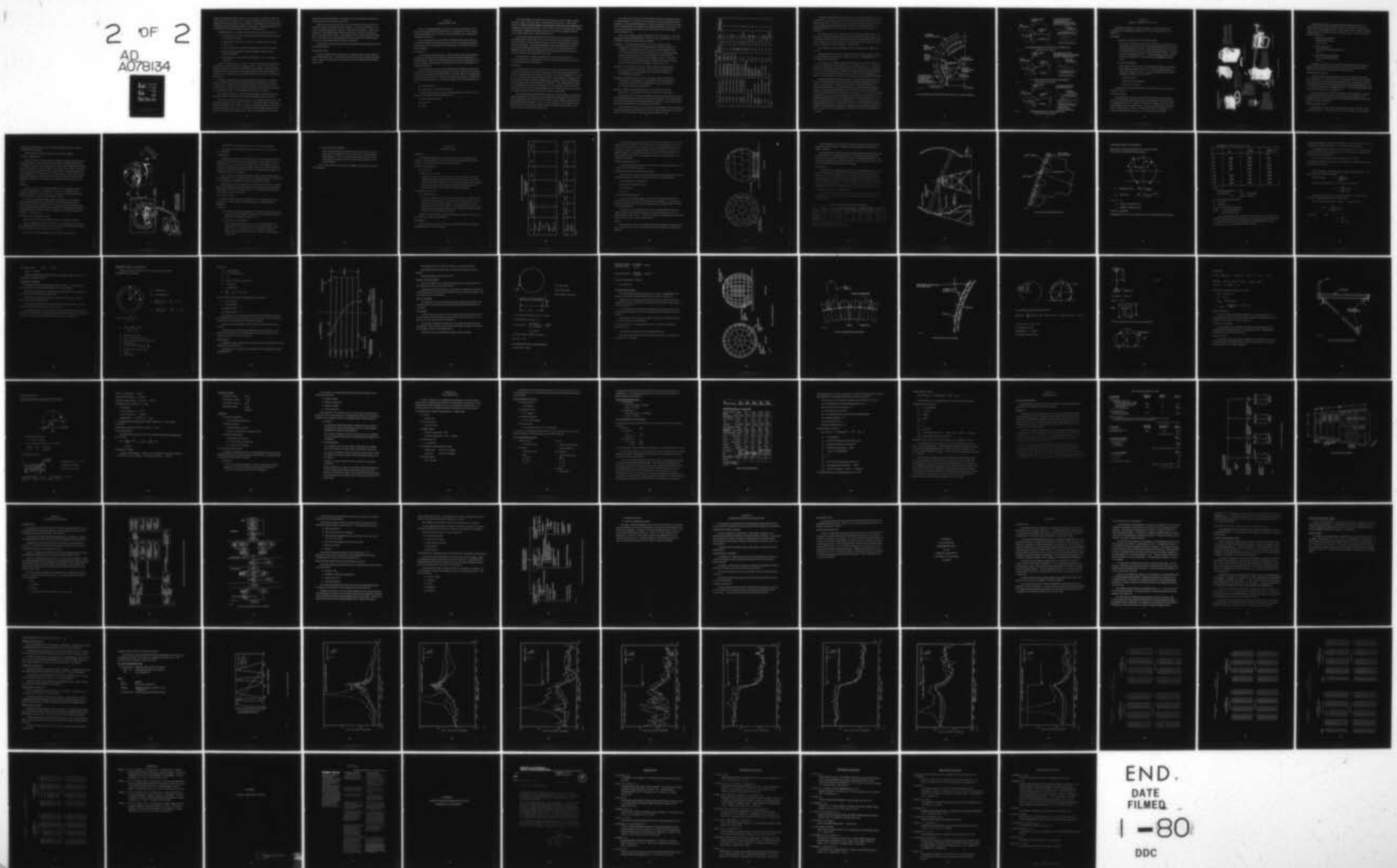

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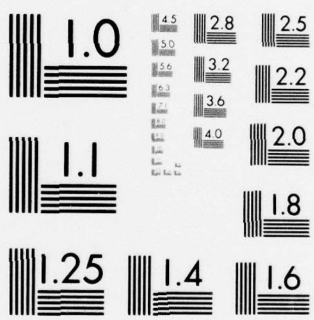

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design to tradeoff the collimation angle, size of collimators, number of collimators, jitter control, center of rotation, etc. Therefore the trades are limited to the more fundamental factors applicable to the approaches. The technology used in both systems is feasible and neither approach requires new technology. The specific problems and drawbacks come from the fundamental geometry or physical laws.

A suitable baseline is a directly gimballed collimator system that provides:

- 1 solar constant in a 36 x 44 inch region when illuminated from the zenith, for each solar simulator
- Programmable stops in each collimator to confine illumination to the cockpit area
- Relative translation provided for collimators on the support structure
- Local illumination system to conceal collimator structure and the supporting structure
- One simulator per crew station respositionable to service all cockpit geometries.

Using a 30 KW Xenon short arc source, a solar constant can be delivered to the cockpit with a collimation angle of ± 2 degrees or less. The basic solar simulator would be modeled on Spectrolab's XM-300 Xenon Source Module. The Spectrolab design consists of a projection head, power supply cabinet, and a module controller. A cooling unit is available which provides chilled demineralized water to cool the Xenon lamp housing.

The CSDF solar simulator will require at least two projectors. It will also require mechanical control of the projected intensity to simulate the sun when it is near the horizon and color filters to simulate the shift to red as the number of air masses increase. Shutters are also required to prevent a crew member from seeing two overlapping sun discs. These provisions would be servo controlled.

The ± 2 degree collimation will provide minimal shadow distortion and the performances of sun rejection filters used on cathode ray tubes will not be affected.

The dome was sized to permit the sun to rise or set behind the terrain pan. This feature will accentuate the oversized solar disc. As the sun elevation is reduced the perceived intensity is also reduced. As a result a controllable aperture can be used to reduce the collimation angle. This will provide the correct angular appearance and reduce the intensity of the "sunlight" by the ratio of the simulated sun's initial solid angle to the projected solid angle. The reduced intensity would also be colored by a subtractive filter to simulate the correct hue.

When the sun rises in the sky, the size of the apparent sun must be allowed to increase in order to provide the correct irradiance. At these times the crew is less likely to routinely look directly at the sun. The natural sun subtends + $\frac{1}{4}$ degree, but looking into a substantially larger angle centered on the sun's disc will cause pain. This is caused by forward scatter. The photometer scan in Figure 16 illustrates this effect. The field of view of the photometer scanning across the sun would not result in so broad a spike unless substantial scatter was present.

All of these provisions represent high technology engineering, but they can all be readily implemented.

MOON SIMULATION

The solar simulators that would present a collimated image of the sun could be used to simulate the moon. A second focal plane would be used to introduce the moon's image. The primary focal plane can be used to control the illumination level falling on the cockpit.

SECTION V

TERRAIN SIMULATION

The term "terrain simulation" is used here to describe that area of study which will attempt to define the requirements for simulating the "out-the-window" visual scene including: desert, forest, urban and suburban areas, landing fields, mountains and seascapes.

It is understood that while the faithful reproduction of the visual scene is a much desired design goal, the highest priority must go to realistically simulating the illuminance levels experienced in the cockpit under varying external environmental conditions.

BACKGROUND

At the beginning of the last decade, cockpit simulators had been developed to a point where the dynamics and response to pilot inputs could be duplicated in a realistic fashion. At that time, little had been done in the way of developing realistic out-the-window visual displays and attempts to overcome that deficiency were rapidly being pursued.

These new attempts to increase the fidelity of the simulators by introducing external visual cues met with varying degrees of success. Most of the developments taking place were directed at trying to achieve a favorable trade-off or compromise in those parameters which were considered essential to achieving a reasonable level of fidelity of the external scene. The desired characteristics normally considered were:

(1) The field of view

(2) Image quality - contrast and resolution

(3) Image illumination (as a relative usable quantity rather than as a reproduction of real world absolute illumination levels)

(4) Stereoscopic perspective

(5) Eye relief

(6) Color.

The visual displays developed were represented by a diverse range of configurations: closed circuit television, both black and white and color, using model boards or computer generated inputs; projected films; point light source reflective and transparency projections and others. None of these, however, addressed the problem of operation in a highly illuminated environment, but were all designed to operate in low ambient light levels, usually darkened areas.

Today, with the increasing workload on the pilot and crew to perform necessary tasks, factors which before were considered of secondary importance become primary effectors in determining the maximum effective workload that the pilot and crew can accomplish. The ambient lighting and cockpit illumination now become a major factor in determining optimum cockpit design. It is desired then to have available a facility which will simulate these external illumination levels for man-machine evaluations in a controlled environment.

It is the purpose of this task assignment to define the requirements for "terrain simulation" to supplement the primary facility design features of realistically replicated sky and sun illuminance.

DISCUSSION

A comprehensive survey was conducted of available literature to determine the availability of systems or technology developments which offer the characteristics to satisfy the requirements for a "terrain simulator" for the CSDF (References 1-33 and 35-42). A similar survey had been made in 1965 for visual displays, in general, for the National Aeronautics and Space Administration, Houston, Texas, by the Farrand Optical Company, Inc. under Contract No. NAS9-3698. This study made by Farrand was probably the most extensive investigation of visual displays at that time and the compilation of those results are still applicable today. There have been some display developments since that time but not in the area of new approaches.

The Farrand study included television systems, mosaic systems, motion picture systems and others. Since the time of that study, the developments in increased display capability have been in the areas of resolution, picture quality, computer/image generation and color rendition. As far as can be ascertained, no developments have been made in the area of terrain simulation in high ambient light conditions. Reference sources are listed in the bibliography.

The present state of the art as determined by thorough investigation precludes the implementation of a realistic "terrain simulation" in the high ambient lighting conditions. Using the latest techniques for visual presentation of the out-the-window scene would necessitate the dimming of the background lighting to night-time levels. This would compromise the purpose of the CSDF which is to provide realistic ambient lighting levels.

None of the candidate systems as indicated in GAC "Proposal for a Crew Station Design Facility Feasibility Study", Section 2.7 meet the criteria for "Terrain-Simulation" under high ambient lighting conditions:

Approach 1 - Terrain model tracking TV camera and projection system. Lighting levels are too low for CSDF purposes. Maximum light levels available in an existing system are 5 to 8 foot lamberts brightness on a 29 foot radius cylindrical screen. This system uses computer generated images projected on the screen with an Eidophor projector which has been especially optimized for maximum brightness levels. This system is in operation at the CAORF (Computer Aid Operating Research Facility) facility at the Merchant Marine Academy in Kings Point, N.Y.

Approach 2 - An engraved dome with an internal light source and capable of two (or more) degrees of freedom. This has been successfully used in a darkened room, but the light levels necessary for utilization in the CSDF cannot be achieved.

Approach 3 - Multiple projectors similar to technique used at ITT pavilion at Disneyland. This approach is not adaptable to real time simulation, is limited to so-called 'canned' problems and in any event would not meet the high illuminance requirements.

Approach 4 - IMAX; a wide angle projection system using 70 mm motion picture film. This approach has the same limitations as Approach 3.

The state of the art in various type displays which are either presently in use or have been investigated for potential use is presented in Table 15. The table presents some of the more important use parameters and cost factors, as well as an indication of its possible applicability to the CSDF simulation facility.

Of the described systems, none meets the required brightness level requirements. Those systems which are described in the table as having "high" brightness are in the range of 5 to 10 foot lamberts, well below a usable brightness level.

Table 15 Review of Simulation Visual Display

	DISPLAY TYPE	IMAGE GENERATOR	IMAGE PRESENTATION	FIELD OF VIEW	RELATIVE BRIGHTNESS	SIZE	REL. COST	APPLICABILITY TO CSDF - HIGH AMBIENT
1.	TELEVISION	COMPUTER GENERATED	TV MONITOR/VIRTUAL IMAGE- - FRESNEL LENS	$>180°$ HORIZONTAL	MED.	MED.	HIGH	NO
2.	TELEVISION	COMPUTER GENERATED	SCHMIDT PROJECTORS ON PANORAMIC SCREEN	$>180°$ HORIZONTAL	LOW	MED.	HIGH	NO
3.	TELEVISION	COMPUTER GENERATED	EIDOPHOR PROJECTORS ON PANORAMIC SCREEN	$>180°$ HORIZONTAL	HIGH	LARGE	VERY HIGH	NO
4.	TELEVISION	COMPUTER GENERATED	TV MONITOR/VIRTUAL IMAGE- - PANCAKE WINDOW	$>180°$ HORIZONTAL	VERY LOW	MED.	HIGH	NO
5.	TELEVISION	MODEL/PROBE/CAMERA	TV MONITOR/VIRTUAL IMAGE- - FRESNEL LENS	$< 90°$	MED/ LOW	MED.	MED.	NO
6.	TELEVISION	MODEL/PROBE/CAMERA	SCHMIDT PROJECTOR	$< 45°$	LOW	MED.	MED.	NO
7.	TELEVISION	MODEL/PROBE/CAMERA	EIDOPHOR PROJECTOR	$< 45°$	MED.	MED.	MED./HIGH	NO
8.	TELEVISION	MODEL/PROB/CAMERA	TV MONITOR/VIRTUAL IMAGE- - PANCAKE WINDOW	$< 70°$	VERY LOW	MED.	MED.	NO
9.	MOTION PICTURE	FILM	MOVIE PROJECTION ON A SCREEN	$< 90°$	HIGH	LARGE	VERY HIGH	NO
10.	MOTION PICTURE	FILM	VIRTUAL IMAGE PROJECTION	$< 90°$	HIGH	LARGE	VERY HIGH	NO
11.	POINT LIGHT SOURCE	TRANSPARENCY	OVERHEAD, FRONT PROJECTION.	$>180°$	MED.	MED.	LOW	NO
12.	POINT LIGHT SOURCE	REFLECTION PLATE	REAR SCREEN PROJECTION	$60°$	LOW	SMALL	LOW	NO
13.	LASER TV	COMPUTER GENERATED	LASER TV PROJECTOR	$<120°$	HIGH	LARGE	VERY HIGH	NO
14.	LASER TV	LASER TV CAMERA	LASER TV PROJECTOR	$<120°$	HIGH	LARGE	VERY HIGH	NO
15.	MOSAIC	COMPUTER GENERATED	MOSAIC	$360°$	HIGH	MED.	EXTREMELY HIGH	NO

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It should be noted that almost all of these systems could be implemented as part of the CSDF in a darkened environment and within the constraints imposed by the other design considerations. However, there are many existing facilities which already provide this capability and the inclusion of this capability (at limited light levels) was deemed inappropriate to the main systems usage which is high ambient light level simulation.

Sky lighting levels can be variable from zero to maximum through suitable programming. By extending this programming to accommodate the terrain lighting level requirements and by also using a translucent horizon pan of appropriate transmissibility, the lighting levels of the terrain can be controlled with the same lights and lighting system as those used for the sky lighting. (See Figure 37).

This technique, of course, precludes the use of an internally sky lighted dome system.

Brightness level control of the lights behind the horizon pan to provide a simulation of the lighting levels existing on a reflective terrain, is recommended in lieu of providing the real world scene.

The amount of sky lighting reflected off the terrain will vary from 7 percent to 70 percent depending on the type terrain flown over (forest, desert, etc.). Making the horizon pan, which has been proposed for pitch and roll visual cues, of a translucent plastic with a transmissibility of 70 percent, the brightness level of the lamps behind the pan at any given aircraft orientation can be varied from full sky brightness to 10 percent of sky brightness to give the 10 to 1 change in the terrain reflected illuminance.

One possible difficulty with this approach is in the blending of sky-horizon line-terrain color levels because of the finite width of the primary illumination lamps behind the translucent dome. Attempts can be made to alleviate this situation by a method we will designate as "proportional occulting". By this method, the lamps for normal sky illumination for the conditions to be simulated will be set at the desired level when not blocked off by the horizon pan, as in Figure 39. As this lamp is occulted by the horizon pan, the lamp will be proportionally adjusted so that when the lamp is completely occulted as in Figure 38 the lamp light level and color will be set at a level which will exhibit the desired terrain illuminance level. Figure 40 shows one intermediate occulting position. (The example shown is for a sky illuminance level which is 50 percent of the maximum attainable lamp brightness and the terrain reflectance is taken as seven percent of sky illuminance. The horizon pan has a transmissiblility of 70 percent).

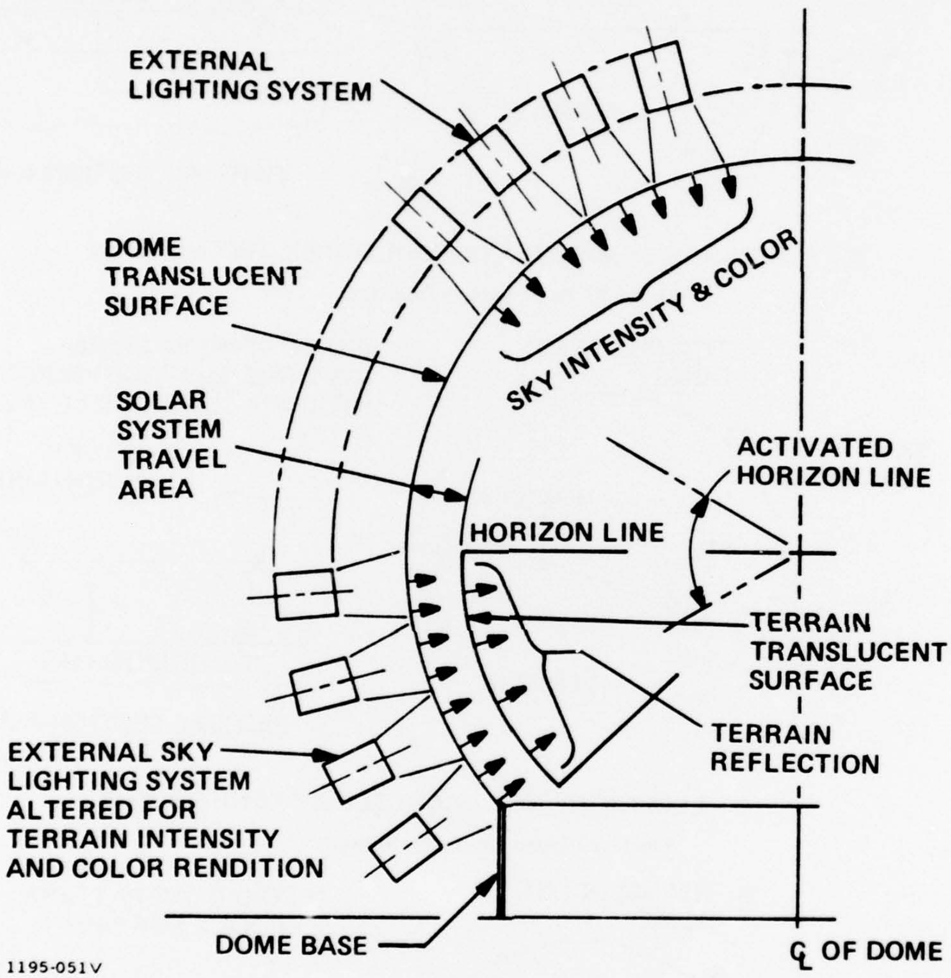
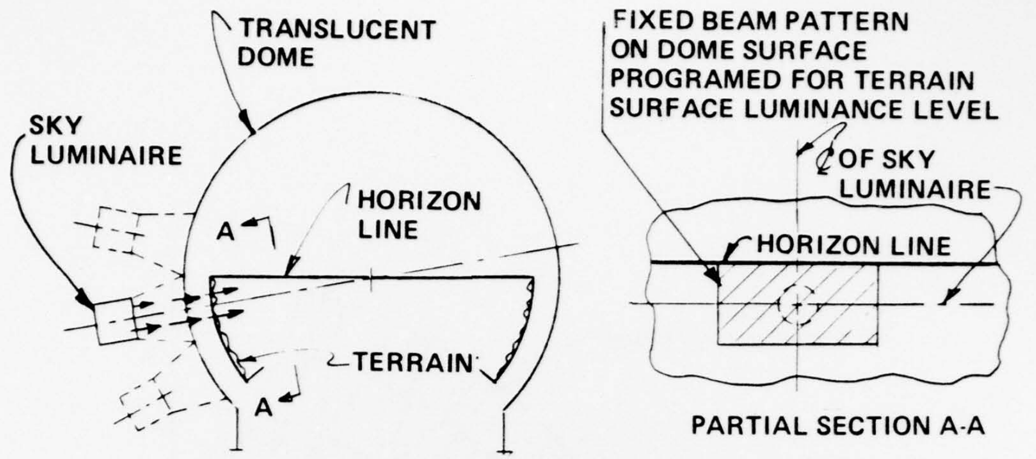


Fig. 37 High Ambient Terrain Reflection With External Sky Simulation – Baseline Configuration



A - LUMINAIRE COMPLETELY OCCULTED BY TERRAIN PAN

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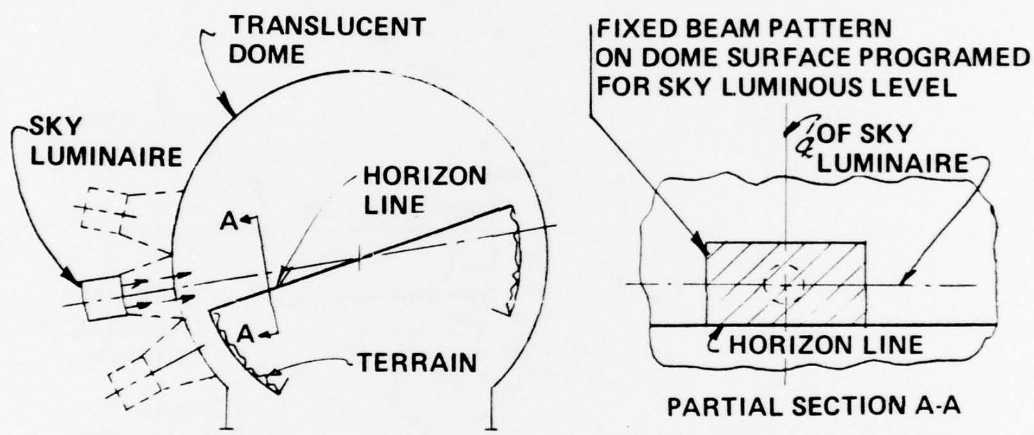
Figure 38. Beam Pattern Occulting



B - LUMINAIRE NOT OCCULTED BY TERRAIN PAN

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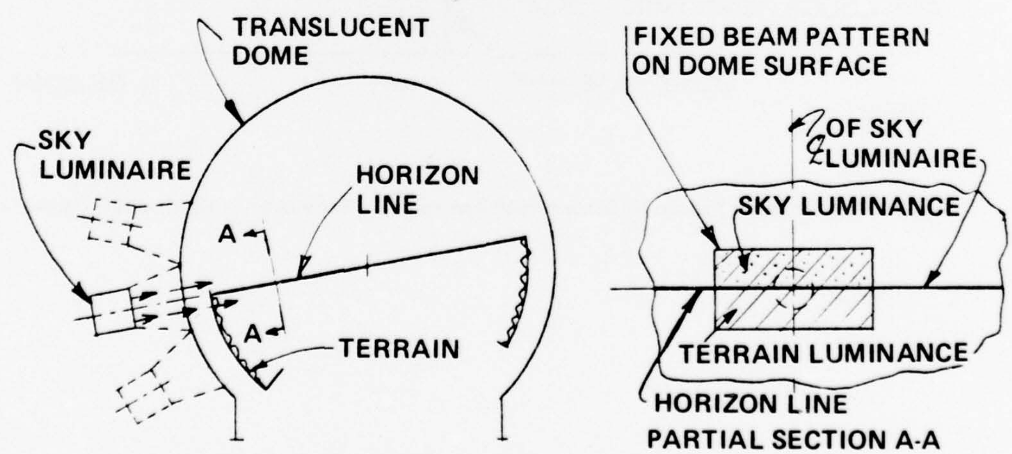
Figure 39. Beam Pattern Occulting



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C-LUMINAIRE PARTIALLY OCCULTED BY PAN

Figure 40. Beam Pattern Occulting

SECTION VI

REDUCED VISIBILITY SIMULATION

Feasibility of Simulation of reduced visibility was studied and defined in accordance with requirements established in the contract SOW, Section F, paragraph 4.6.4.

DISCUSSION

- Approach - Fog, Smoke, Cloud and Mist (FSCM)

  Fog, smoke, cloud and mist generation techniques were studied and it was found that the optimum method for simulating FSCM entails use of mineral oil based generator within which a heat manifold converts oil to smoke and the smoke is conducted to the area within the facility at which it is required for the mission under simulation. This recommended approach is based upon prior investigation of several alternative techniques as indicated below.

- Areas of Investigation

  Initial efforts were directed toward determining methods by which FSCM can be generated. Inquiries and visits to theatrical special effects designers and suppliers were made. It was determined that three primary methods are employed in such simulation:

  - Oil based system
  - Carbon Dioxide based system
  - Smoke Powder system.

Photographs of commercial equipment and products discussed in this report appear in Figure 41.

OIL BASED SYSTEM

Oil based smoke is generated by injecting clear mineral oil into a chamber in which an electrically heated manifold surface converts the oil to smoke when the oil contacts the hot surface. Smoke is generated very rapidly, and can be ejected quite readily by means of solenoid valves. The smoke can be directed toward any large or localized area by means of a suitable duct system. Consequently, its effect can be simulated at the horizon, over terrain or about the cockpit.

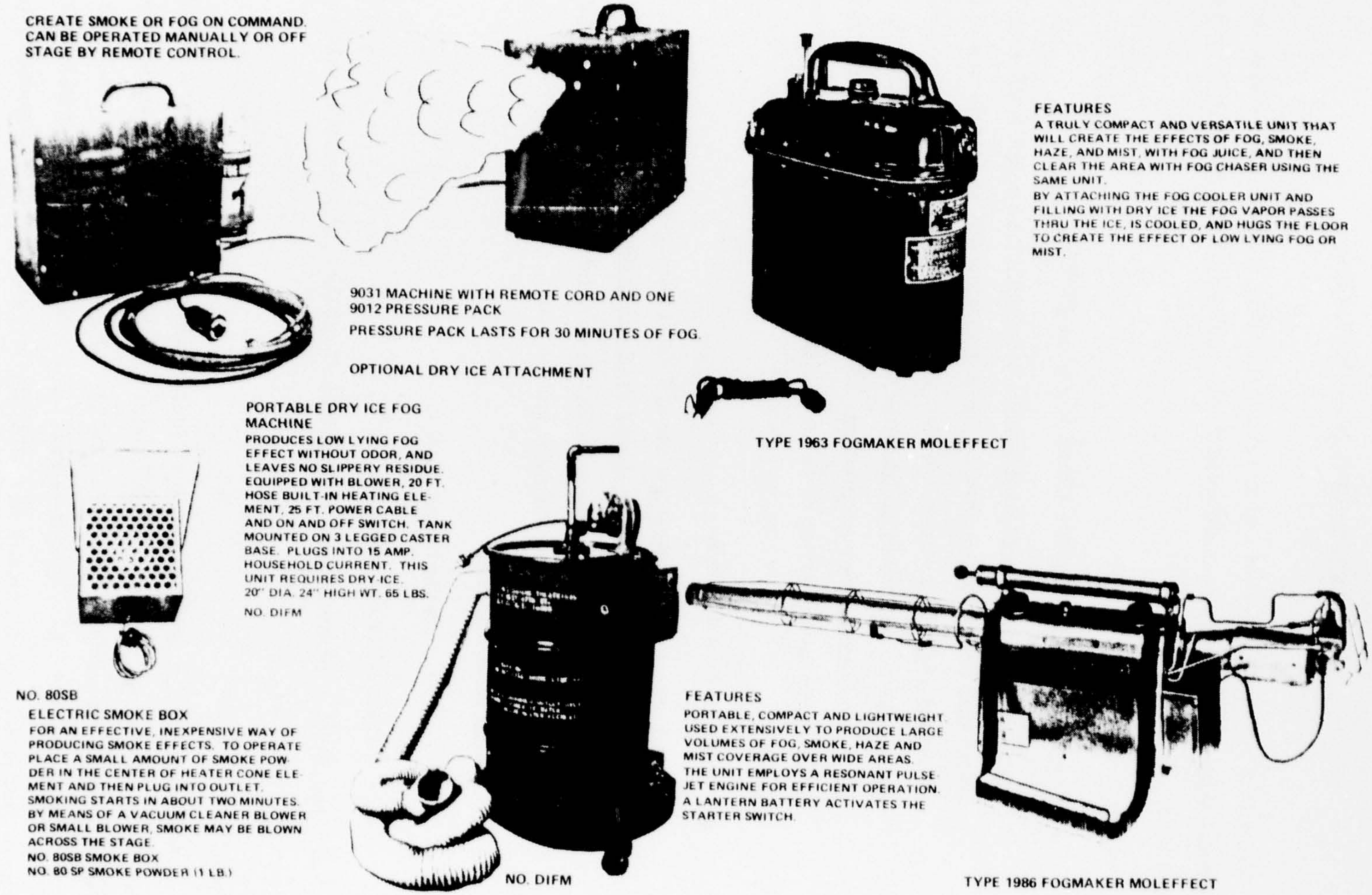

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Figure 41. Various Fog Machines

Commercially available oil generated smoke systems allow some oil to escape into the environment into which the smoke is introduced. This does not seem to be an insurmountable problem. Filters which remove oil while permitting smoke to pass can be readily introduced within the system. Some commercially available systems are:

- Model 9031 Fog Machine
  Mutual Hardware Corp.
  L.I.C., N.Y.

- RMF Fog Machine
  Time Square Theatrical Supply Corp.
  N.Y.C.

- Mole-Richardson Fog Machine
  Chas. Ross Theatrical Supply
  N.Y.C.

It should be noted that it is also quite feasible and perhaps more practical to design an oil based fog generator especially suited to fit and operate within the facility without resorting to purchase at commercial sources.

CARBON DIOXIDE SYSTEM

Carbon dioxide fog machines utilize dry ice. Two methods for generating fog are employed. One is to heat the dry ice contained in a tank and use a pneumatic pump to eject the dry ice fog from the tank into the area in which the fog is utilized. The second method uses water which can be heated to any desired temperature. Dry ice is immersed in the water, generating CO_2 fog. The fog is pumped from the tank to the area in which fog must be introduced.

The water immersion methods adds moisture to the resulting fog. Therefore, use of desiccant between the generator and the simulator environment will be necessary in order to avoid the destructive effect on CSDF mechanisms which would result from excessive moisture.

SMOKE POWDER SYSTEM

Smoke powder is a pulverized crystalline material which is fed into a heated chamber within which it reacts to produce a heavy white smoke. The smoke thus generated can then be pumped to the area within the CSDF in which the reduced visibility effect is to appear.

Smoke powder is available through theatrical effects suppliers.

CONTROL & DISPERSION

Once the smoke is introduced within the CSDF environment, methods must be devised by which the degree of dispersion, localization, containment and density is controlled. Ability to achieve the necessary control will be affected by the extent to which air within the dome is circulated or maintained static. Static air facilitates control in localization of FSCM reduced visibility effects. Moving/circulating air will necessitate use of transparent devices for containment and prevention of rapid uncontrolled dispersion. It will also be necessary to determine methods by which undesirable reflections from transparent fog containment enclosures can be prevented.

TOXICITY

The three processes for generating FSCM have been extensively used for theatrical special effects. Apparently their use has been regarded as safe for personnel working in the same environment. However, it is preferrable that the question of toxicity be reviewed and investigated in depth.

The Civil Aero-Medical Institute (CAMI), Department of Transportation Federal Aviation Administration, Oklahoma City has conducted many tests to evaluate emergency interior lighting systems of both narrow and wide body transport aircraft under simulation fire/smoke conditions. The attached letter specifies the equipment they are using for smoke generation which can also be used for fog simulation. See Appendix C.

INTRODUCTION & REMOVAL OF FSCM

Introduction of FSCM into the CSDF will present no significant problems.

Tanks, manifolds and pumping systems will be remotely located. Ducts will carry FSCM under the facility floor to a section below the cockpit simulator platform and will be hidden from the field of view (see Figure 42).

Ejective jets will inject FSCM beneath the cockpit into the cone area.

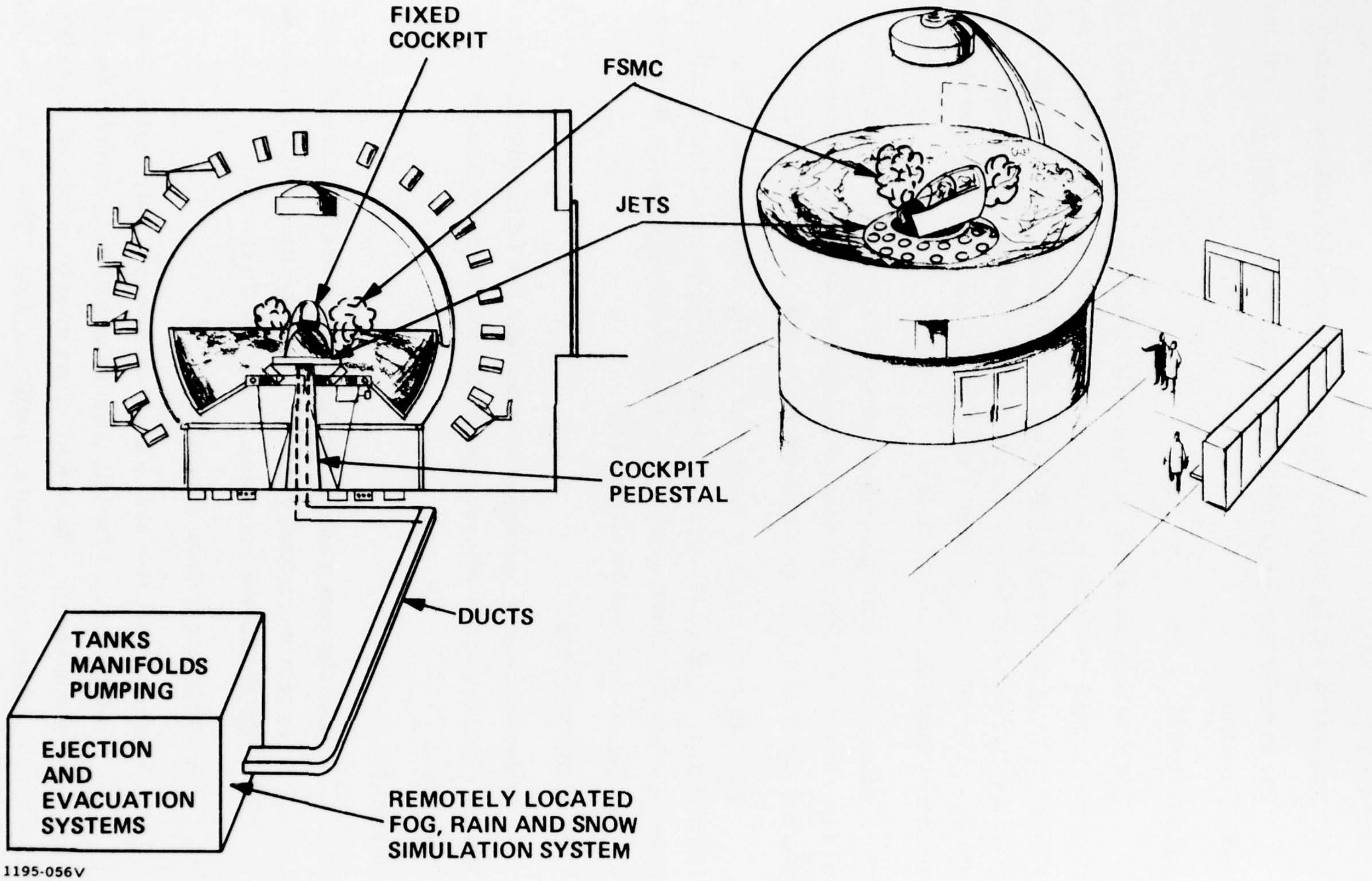

Figure 42. CSDFS Baseline Configuration – External Sky Simulation

Evacuation will be achieved by use of a forced air/exhaust system.

The same or similar parallel duct systems can be used for rain and/or snow simulation.

LIMITATIONS

FSCM simulation within an externally lighted sky dome (baseline configuration) will provide realistic results when operated in a non-activated system (i.e. stationary horizon--no change in roll or pitch angle). This limitation results from the fact that though the apparent relative attitude of the visual surroundings changes, the FSCM cannot shift with respect to the simulated motion unless it is contained within the moving system.

With a mineral oil-manifold generated fog system, exposed CSDF surfaces will be subject to oil film residual deposits after prolonged exposure. This problem was not significant in applications where short exposure was typical.

This difficulty might be minimized or even eliminated by means of a suitable filter system designed to entrap suspended oil particles and pass only uncontaminated smoke. The filter system best suited to this purpose must be determined during detail design and development.

LOW AMBIENT LIGHT

Reduced visibility under low ambient light can be simulated by use of projection systems such as computer generated images or by film projection techniques.

SUMMARY

- Existing materials and techniques now available can readily be adapted to provide reduced visibility simulation under high ambient light for the CSDF with the limitations discussed above.
- Approach to Snow Simulation

  Snow simulation can be achieved by use of polyethelene flakes, the materials used for this purpose may cling to surfaces due to electrostatic charge. Some R&D effort must be employed to study this problem and develop a suitable solution. This can be done during the design phase.

- Approach to Rain Simulation

  Rain simulation techniques including water and/or solids were investigated and it was found that the best material will be solid transparent beaded particles. This is necessary because the use of water will be detrimental to actuating mechanisms which would be subject to corrosion and damage.

A duct system similar to the one used for FSCM can be utilized for snow and rain simulation.

SECTION VII
DOME STRUCTURE

BASELINE

Two baseline configurations were established for the Crew Station Design Facility. These configurations, internally illuminated and externally illuminated, determine the requirements for their associated enclosures.

INTERNAL ILLUMINATION

- Opaque Dome
- Reflective inner surface

  Conventional framed structures fulfilling these requirements are readily available and could be designed and procured in the materials evaluated in Table 16. However, constraints on this baseline imposed by other considerations (see Section II) obviated the need for further investigation and the effort was directed to the externally illuminated configuration.

EXTERNAL ILLUMINATION

- Translucent Dome

  To meet the requirements of providing an acceptable sky simulation with an external illumination source, a translucent dome structure must be placed between the luminaires and the cockpit. The dome structures' primary function is to act as a uniform diffuser of the multiple luminaire light source while transmitting maximum luminosity and obscuring all external framing, support structure and ancillary equipment.

Table 16 lists the alternative types considered and the ratings given for the primary function are briefly described below.

INFLATABLE:

This construction consists of a thin air-supported shell of the type currently manufactured by the 'Bird Air' company.

Table 16 Dome Structure Material Tradeoff

External Sky Illumination
Translucent Dome

TYPE	LIGHT TRANSMISSION		FABR. S-O-T-A	MAINT.	TEMP.	RECOM.
	UNIFORM	%				
INFLATABLE	P	G	G	F	G	
RIGID SELF SUPPORTING						
ACRYLIC	G	G	G	G	F	√
POLYCARB.	F	G	F	P	G	
FIBER GLASS/ PLASTIC	P	F	G	G	G	
RIGID FRAMED STRCT.	P	G	G	G	G	

Internal Sky Illumination
Opaque Dome

TYPE	SURFACE	FABR.	AVAIL.	MAINT.	TEMP.	RECOM.
ALUMINUM	G	G	G	G	G	√
FIBER GLASS/ PLASTIC	G	G	F	G	G	

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The size and shape of the structure is well within the state-of-the-art. A vinyl-dacron material is available that will provide 85% light transmission in its uncoated form and 70% when coated. It is claimed to have long service life and good flame resistance. However, a significant problem exists in achieving the uniformity of diffusion required. The construction technique results in 2-inch wide seams at 50-inch spacing that will result in unacceptable patterning on the inside surface when externally illuminated.

RIGID FRAMED STRUCTURE

A rigid framed structure with translucent panels is also unacceptable due to the visibility of the framing and supports.

RIGID SELF-SUPPORTING SHELL STRUCTURES

This approach of using a self-supporting shell in the area of the field of view will provide the necessary uniformity of luminous transmittance and diffusivity.

Three materials were investigated:

- Glass fibre reinforced plastic
- Polycarbonate
- Acrylic.

Glass Fiber Reinforced Plastic

To achieve an acceptable degree of light transmission and uniformity it is desirable to fabricate this under heat and pressure in an autoclave. This predicates a panel construction for which no edge bonding technique is possible which will meet the criteria established.

An alternate is to develop an automated spray technique which will deposit a uniform thickness of chopped strand fiber in a plastic base onto a male form tool representing the complete shell. To achieve the uniformity of dispersion is considered beyond the state-of-the-art on the scale required.

Acrylic

An acrylic dome structure is proposed using preformed panels of approximately 10' x 10' that are edge bonded to form the spherical shape required as illustrated in Figure 43.

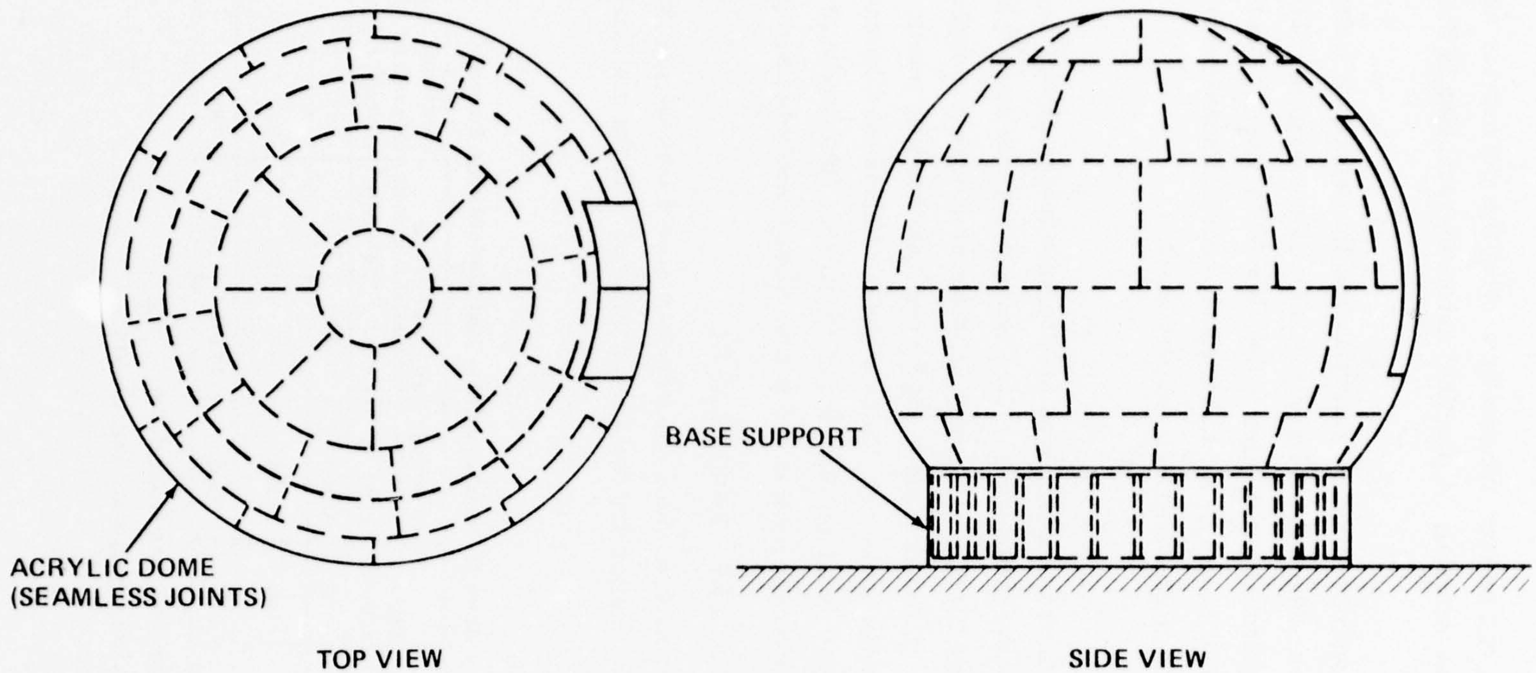

Figure 43. Translucent Dome Fabrication Technique

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Edge bonding can be accomplished by casting the gap between adjacent panels using the same base material. A practical assembly technique is illustrated in Figures 44 and 45.

Discussions with Swedlow Inc ascertain that this approach is feasible and within the state-of-the-art. The material would be a commercial grade of cast acrylic sheet such as a pigmented formulation of Swedlow 310 (Federal Standard 391). The joint casting material should be a totally reactive acrylic adhesive of the Rohm & Haas PS30 type that is pigmented to match the cast sheet.

Polycarbonate

Polycarbonate was considered as an alternate material utilizing the same fabrication technique as described for Acrylic. Several aspects make this a high risk approach. The edge bonding of the polycarbonate cannot be accomplished using a casting technique. A solvent bond would be required and this entails keeping the edges in contact under pressure. Under these conditions the tolerance on the panel trim and fit become crucial and is a major constraint. Polycarbonate sheet is not available in the thickness required and fusion bonded laminates would be needed.

PRELIMINARY ANALYSIS - RIGID PLASTIC

Preliminary analysis of a shell structure shows that the predicted hoop stress levels due to its own weight are low when compared with the material properties shown in Table 17.

Table 17 Translucent Dome Rigid Plastic Material Properties

CANDIDATE MATERIAL	MAX OPERATING TEMP °F	SPECIFIC GRAVITY	AV. TENSILE STRENGTH LB/IN.^{2}	AV. COMP STRENGTH LB/IN.^{2}	FLEX MODULUS 10^5 LB/IN.^{2}	TH. CONDUC. 10^{-4} CAL-CM/SEC-CM^2-°C	THERMAL EXP. CO-EF. 10^{-5} IN/IN/°C	LIGHT TRANSMISS. % ≠
ACRYLIC	200°	1.19	10,500	19,000	4.5	1.16	3.9	92
F/GLASS REINFORCED EPOXY*	250°	1.82	15,000	–	25	2.3	2	Ω 80
POLYCARB.	260°	1.2	9,500	12,500	5.0	1.41	3.8	86

*MILLED FIBER REINFORCING IN CLEAR EPOXY RESIN

≠WITHOUT DIFFUSION COATINGS OR SURFACE TREATMENTS

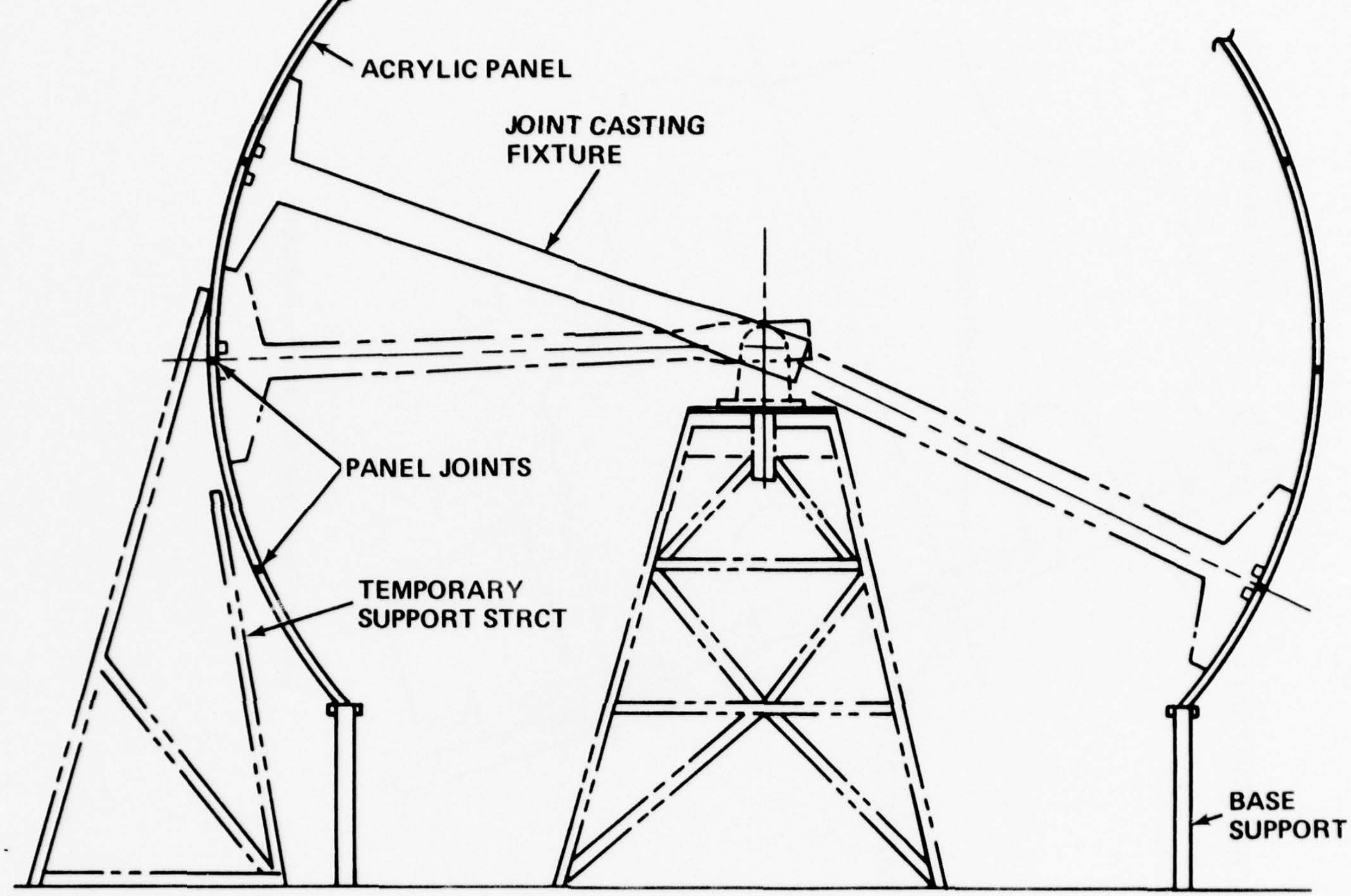

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Figure 44. Dome Panels Assembly Technique

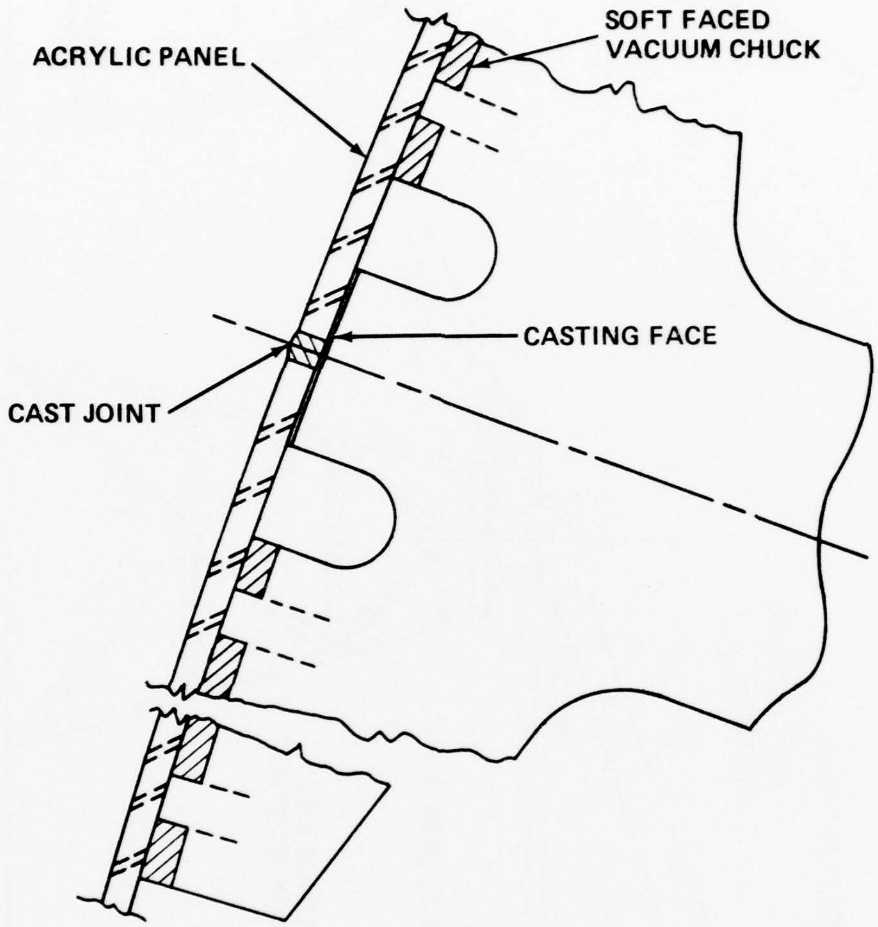

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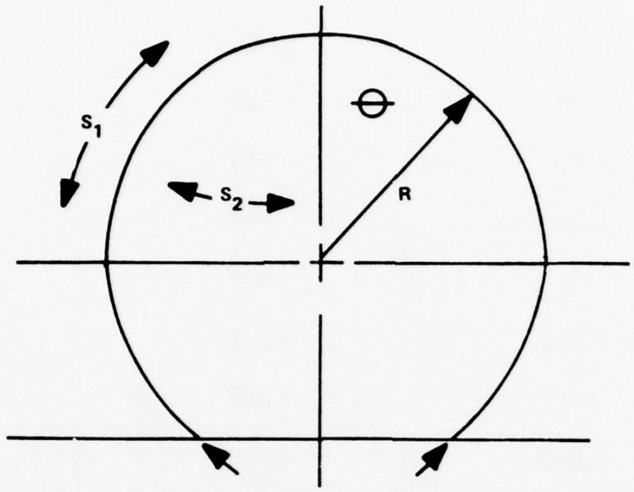
Figure 45. Dome Panels Seam Bonding Techniques

Preliminary Analysis - Shell Thickness

Stress levels in thin spherical shells due to their own weight

Ref. Roark - Formulate for Stress and Strain



S_1 = Meridianal Stress $= \frac{-Rw}{t} \left(\frac{1}{1 + \cos\theta} \right)$

S_2 = Hoop Stress $= \frac{Rw}{t} \left(\frac{1}{1 + \cos\theta} - \cos\theta \right)$

where $w = \alpha t$

α = weight of material lb/cu in

t = thickness of shell in inches

Supports are tangential.

Substituting αt for w it can be seen that the stress is independent of the thickness.

Evaluating for a shell where θ max = 130°

$\theta°$	$\cos\theta$	$\frac{1}{1+\cos\theta}$	$\frac{1}{1+\cos\theta} - \cos\theta$
0	1	0.5	-0.5
15	0.9659	0.5086	-0.457
45	0.707	0.5857	-0.121
60	0.500	0.666	+0.166
75	0.259	0.794	+0.535
90	0	1.000	+1.000
105	-0.259	1.349	+1.608
120	-0.500	2.000	+2.500
130	-0.643	2.800	+3.443

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Max Meridianal Stress = -2.8 R

Max Hoop Stress = - .5 R (Compression)

and 3.443 R (Tension)

For A 68 Ft Diameter Acrylic Dome

R = 408 inches

α = .043 lb/cu in

S_1 max = 14.035 lb/in^2 Compression

S_2 max = 8.772 lb/in^2 Compression

60.404 lb/in^2 Tension

From the preceding it can be seen that the stress levels due to the shell's own weight are relatively small when compared to the material properties listed in Table 17. Since these stress levels are independent of the shell thickness some other criteria must be used to establish the required thickness.

As the elastic stability is a function of the stiffness of a thin shell, this was used to establish the thickness. (Ref. Roark - Formula for Stress and Strain).

A loading equivalent to 10 times its own weight was used. From experience it can be shown that stress in a structure due to its own weight is typically 10% of the stress due to the applied loads.

For a 68 ft. dia. dome the required thickness is 5/8 inches.

Deriving Shell Thickness Based on the Elastic Stability of a Thin Sphere, Material Properties and Geometry

Elastic stability of a thin sphere under a uniform external pressure - Ref. Roark Formulae for Stress and Strain

Critical Pressure $$P' = \frac{2\,Et^2}{r^2\sqrt{3(1-v^2)}}$$

Using recommended factor of 4 for Geometric irregularity

$$P' = \frac{Et^2}{2\,r^2\sqrt{3(1-v^2)}}$$

Assuming that the stress levels due to a structure's own weight usually account for approximately 10% of the design loading

Then P critical should equal 10 w where w = weight/sq inch $= \alpha t$

$$10\,\alpha t = \frac{Et^2}{2\,r^2\sqrt{3(1-v^2)}}$$

For Acrylic where = $V = .35$

$\alpha = .043$

$E = .45 \times 10^6$

For a 68 Ft. Dome where r = 408 in.

t reqd. = .520 in.

To allow for framing and casting tolerances a nominal .625 in. thick sheet is considered a practical stock size.

Temperature Limitations

Structural temperature limitations are listed in Table 17. At these temperatures the materials retain sufficient stiffness to carry the loading.

When these temperatures are exceeded by approximately 60°F a softening will occur and permanent deformation would result.

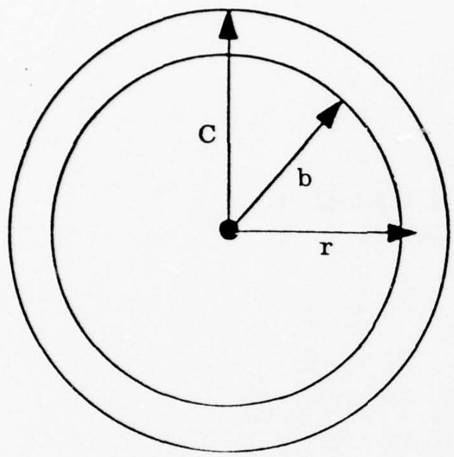
A temperature sensing system will be required to prevent this. This will assure safety aspects listed below.

The change in temperature of the shell structure when heated from one side only will result in thermally induced surface stresses.

The magnitude of these stresses will be dependent upon the rate of temperature change and to avoid surface crazing should not exceed 2000 psi tension. A preliminary analysis of thermal stress indicates this will be approximately 12°F/sec.

Preliminary Analysis - Thermal Stress

Using expressions for thermal stresses in a hollow sphere - Roark Formulae for Stress and Strain



S_r = Radial Stress

S_t = Tangential Stress

$$S_r = \frac{E\alpha m}{15A\ (1-V)}\left(-r^2 - \frac{5b^3}{r} + \phi - \psi\right)$$

$$S_t = \frac{E\alpha m}{15A\ (1-V)}\left(-2r^2 - \frac{5b^3}{2r} + \phi + \frac{\psi}{2}\right)$$

when $\phi = \dfrac{C^5 + 5C^2b^3 - 6b^5}{C^3 - b^3}$

$$\psi = \frac{C^5b^3 - 6C^3b^5 + 5C^2b^6}{r^3\ (C^3 - b^3)}$$

E = Modulus of Elasticity

α = Co-ef. of Thermal Expansion

m = Rate of increase of Surface Temperature

V = Poissons Ratio

A = Co-ef of Thermal Diffusivity $= \dfrac{R}{P_S}$

R = Co-ef of Thermal Conductivity

P = Density

S = Specific Heat

For Acrylic

$E = .45 \times 10^6$ lb/in.^{2}

$\alpha = 4.7 \times 10^{-5}$ in./in./°F

$V = .35$

$R = 2.89 \times 10^{-6}$ BTU in./sec/in.^{2}/°F

$P = .043$ lb/in.^{3}

$c = .35$ BTU/lb/°F

$A = \frac{R}{Pc} = 1.92 \times 10^{-4}$ in.^{2}/sec

For 68 Ft Diameter Dome with a Wall Thickness of 5/8 inches

$b = 407.375$ inches

$c = 408.000$ inches

For inside surface $r = b$

For outside surface $r = c$

The evaluation of the expressions used proved to be extremely sensitive to small differences in very large numbers so it was necessary to write a computer program that was structured so as to minimize this effect.

Stresses were calculated for a rate of increase of surface temperature of 1°F/sec.

Actual stresses will be directly proportional to rate of increase. Plot is shown for 68 Ft diameter, with wall thickness of 5/8 inch and rate of surface temperature increase 1°F/sec (see Fig. 46).

Safety Aspects

Appendix B contains information from Rohm & Haas concerning the fire safety aspects associated with acrylic.

The temperature at which acrylic will ignite can be determined using ASTM method D1929-68.

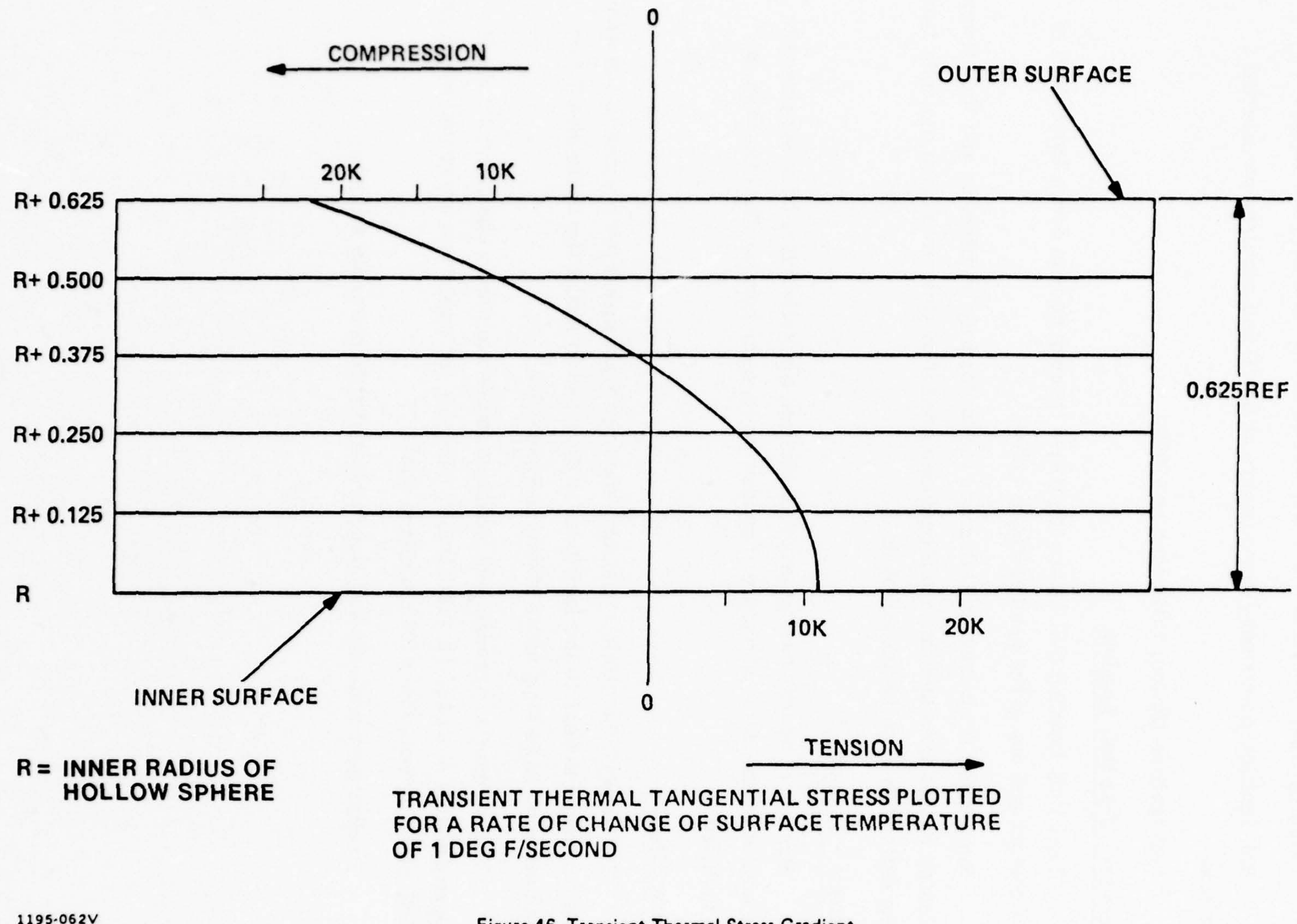


Figure 46. Transient Thermal Stress Gradient

Flash ignition occurs at 572°F and requires an external pilot flame.

Self ignition (temporary glow) occurs at 670°F and requires no external ignition.

Self ignition (flame) will occur at 870°F.

Access - Test Unit Loading

Test Unit Loading will be accomplished through access doors located aft of the cockpit and out of the cone of direct vision.

Supporting framework will degrade the uniformity of diffusion and light transmission in this area and this must be considered if motion simulation methods 1 and 2 as defined in Fig. 12 are adopted.

Access - Personnel

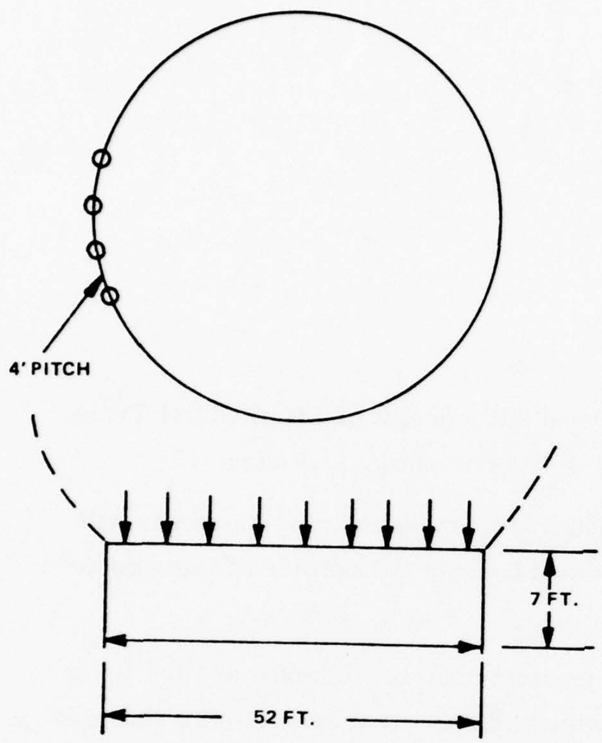
Personnel access can be provided through the cylindrical base support with no impact on the dome structure if access through the horizon/terrain base pan is included.

Base Support

To support the dome enclosure and to provide space for horizon pan motion and personnel access to the facility it is proposed to mount the dome on a 7 foot high circular base support as shown in Figure 43.

The structural arrangement would be to use aluminum channel columns at approximately 4-foot pitch with similar channels for upper and lower rail members. Wall cladding would be 0.04 aluminum sheet.

Preliminary analysis and structural sizing is shown as follows:



68 ft. dia. Dome

5/8" thick Acrylic

Dome Weight = 49,642 lbs

Circumference of support structure = 164 feet

N° of Columns @ 4 ft. Pitch = 41

$$\text{Load per column} = \frac{\text{Wt of Dome}}{\text{No. of Columns}} = \frac{49642}{41}$$

$$= 1210.78 \text{ lbs}$$

Assuming radius of gyration of column = .4

Then $\frac{L}{.r} = 210$

Using Standard Column Formulae (ROARK)

For 6061-T6 Al. Alloy

$$\frac{\text{Allowable Load Q}}{\text{Cross Sect. Area}} = \frac{51,000,000}{(L/r)^2} = 1156.46$$

$$\text{Cross Section Area} = \frac{1210.78}{1156.46} = 1.047 \text{ in.}^2$$

Using 4" Channel with 1" Flanges

t = .174 USE 3/16"

Lamp Mounting Structure

The lamp mounting structure proposed will consist of Longitudinal Truss Members spaced with Latitudinal Ring Members as shown in Figure 47 .

Stiffened sheet metal panels bounded by the truss and ring members will support the luminaires which will be removable from the outside of the structure as shown in Figure 48.

A large degree of commonality of mounting can be achieved and the truss members will be fabricated from common truss section assemblies as shown in Figure 49.

The sizing of the primary truss members will be based on deflection and a preliminary sizing is shown as follows.

Preliminary Analysis - Lamp Support Structure - 80 Ft Dia. Longitudinal Truss Members

Assuming Lamps @ 24" pitch and weighing 60 lbs/ unit.

Each truss is assumed to carry 4 vertical rows of units. This equates to 2 rows/ft. run = 120 lbs/ft.

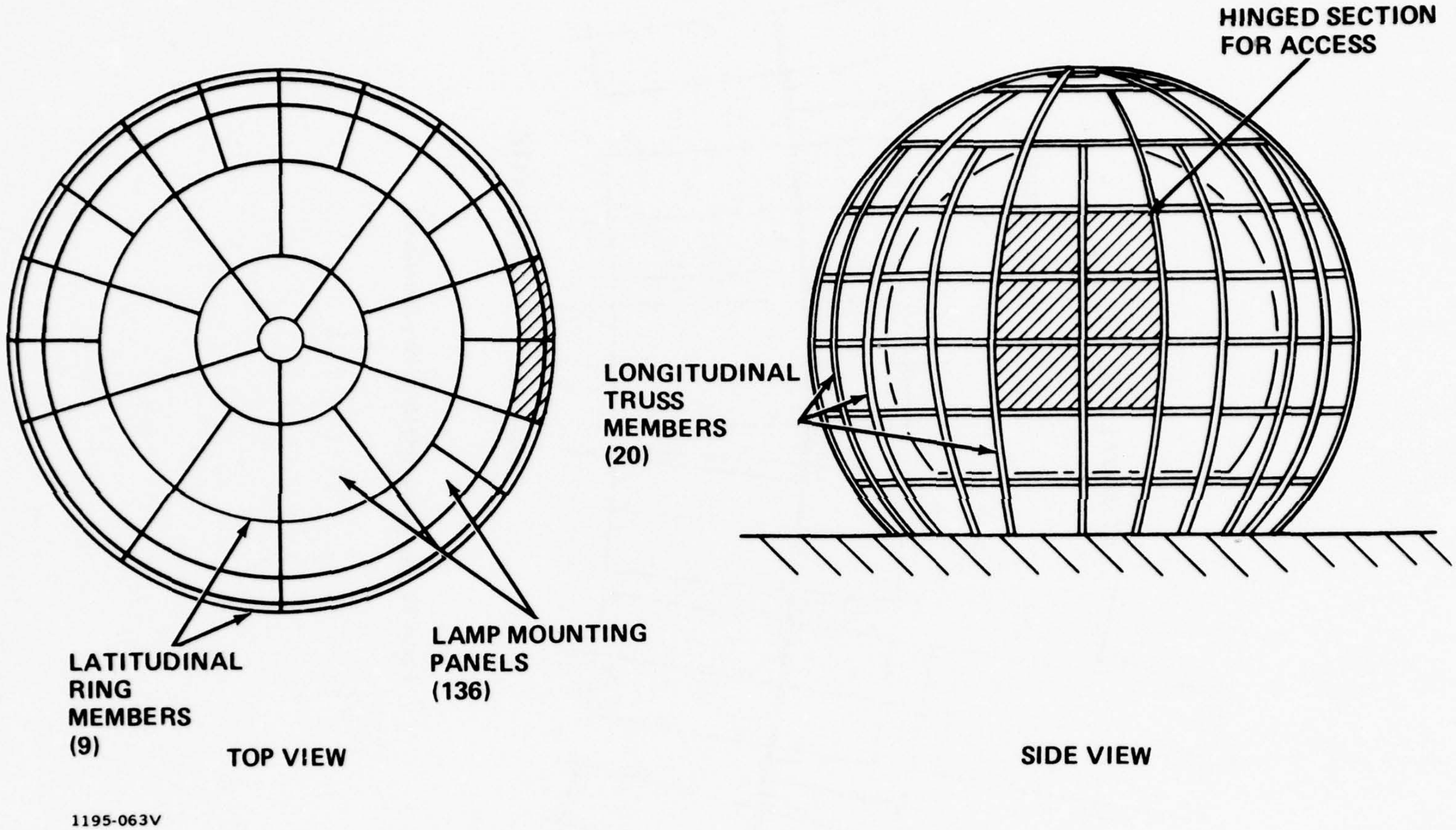


Figure 47. Lamp Mounting Structure

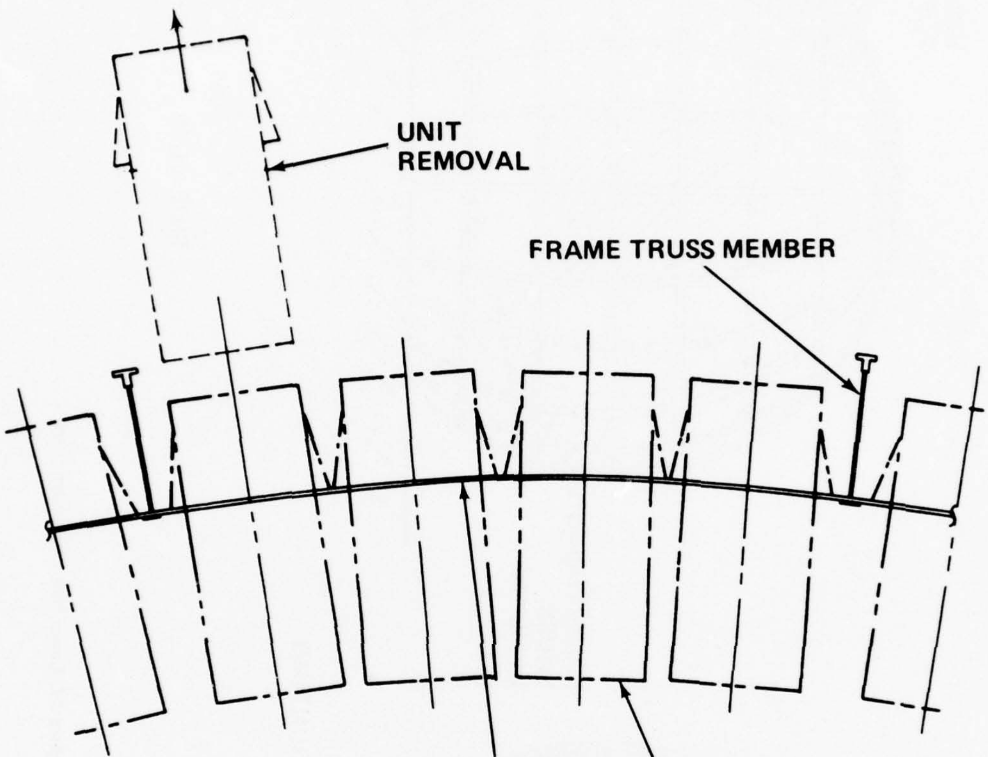


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Figure 48. Lamp Mounting Units (Sky Simulation)

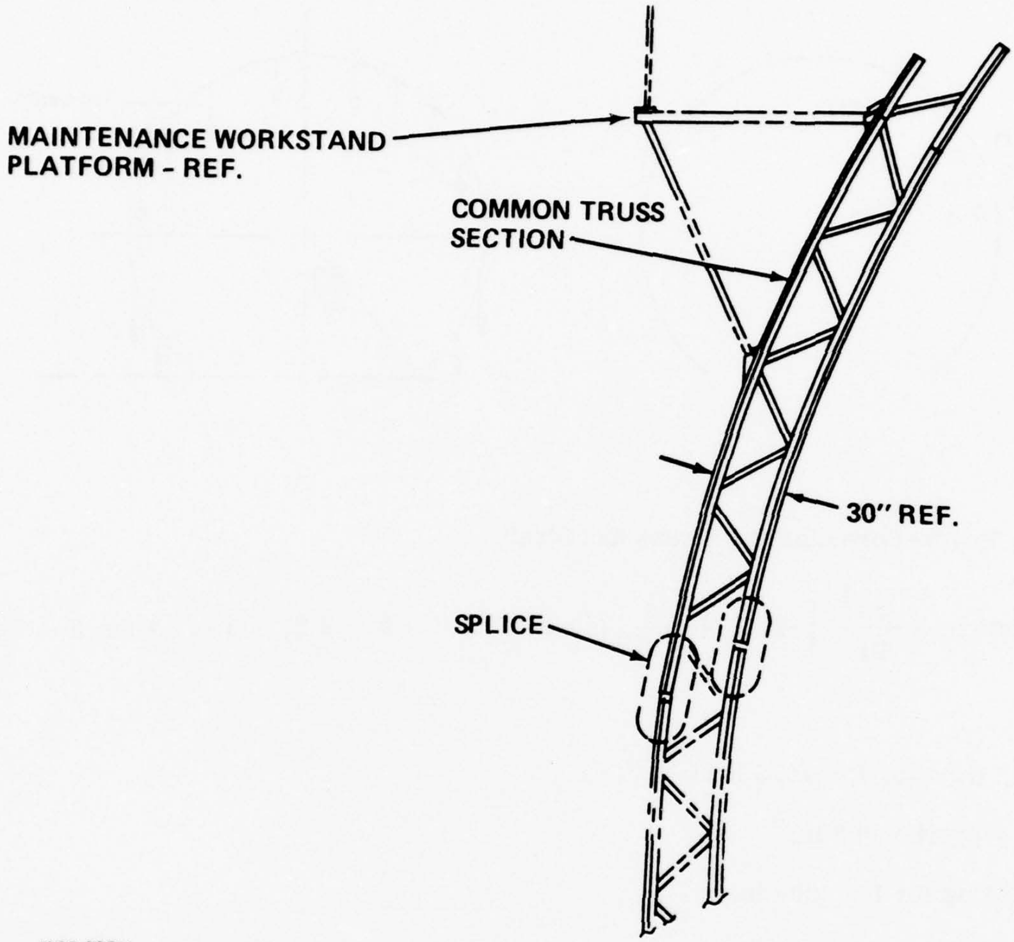

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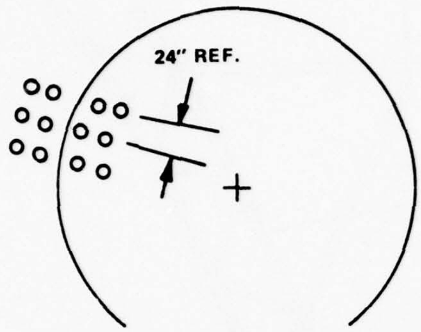
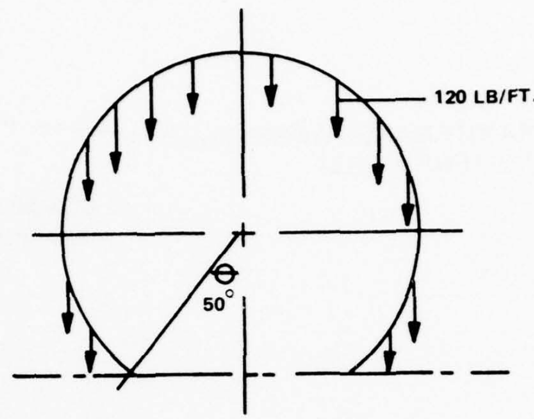
Figure 49. Typical Structure Truss Assembly





Using Roark-Formulae for Stress and Strain

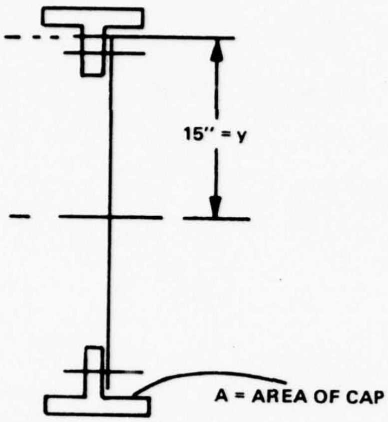
$$\text{Deflection} = \frac{wR^4}{EI}\left[-2.4674 + \frac{\pi}{2}\ (\sin\theta\ \cos\theta + \theta - 2\ \sin\theta) + 2\ (\theta\ \sin\theta + \cos\theta)\right]$$

Using Al. alloy $E = 10.5 \times 10^6$

80 ft support = 900 in.^{4}

Evaluating for I = 900 in.^{4}

Assuming a section as shown

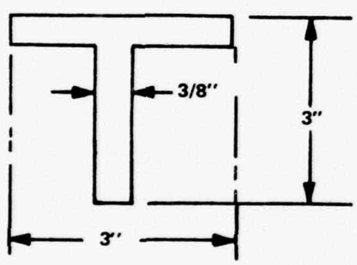


$$I = 2\,Ay^2$$

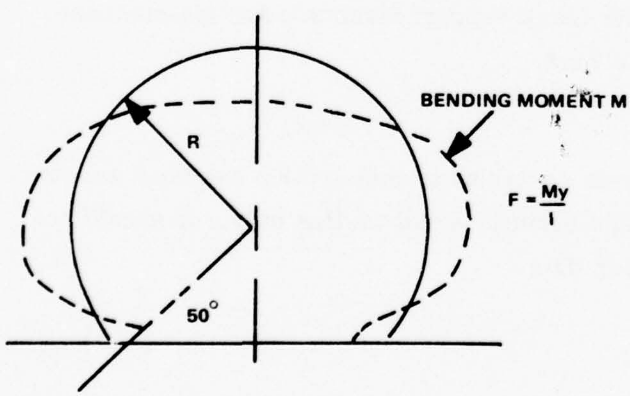
If I required = 900 in.^{4}

Then A = 2 in.^{2}

<u>USE</u>



Checking working stress levels for this configuration.



Using Roark.

$$M = M_1 - T_1R\ (1\text{-}\cos x) + wR^2\ (x \sin x + \cos x - 1 - \pi \sin x + \pi \sin 50)$$

Where $M_1 = wR^2\ (1/2 + \cos\theta + \theta \sin\theta - \pi \sin\theta + \sin^2\theta)$

and $T_1 = wR\ (\sin^2\theta - 1/2)$

For 80 ft. dia. Support structure with 120 lb/ft.

$M_1 = 19{,}123$ in. lb

$T_1 = 417$ psi

$M_{max} = 664{,}600$ in. lb

$$\therefore f_{max} = \frac{664{,}600 \times 15}{900} = 11{,}077 \text{ psi}$$

Workstand Platforms

An array of Maintenance Workstand Platforms will be incorporated in the Lamp Support structure to facilitate servicing. Common workstand sections can be fabricated for this purpose as shown in Figure 50.

Installation and Assembly

It is anticipated, that to facilitate the casting assembly technique used for constructing the translucent shell, the Lamp Support Structure and Maintenance Workstands will be assembled on site first.

Design and Analysis

The degree of design and analysis contained in this section has been accomplished to support the feasibility weight estimates and costing only. It should not be construed in any way as final design data.

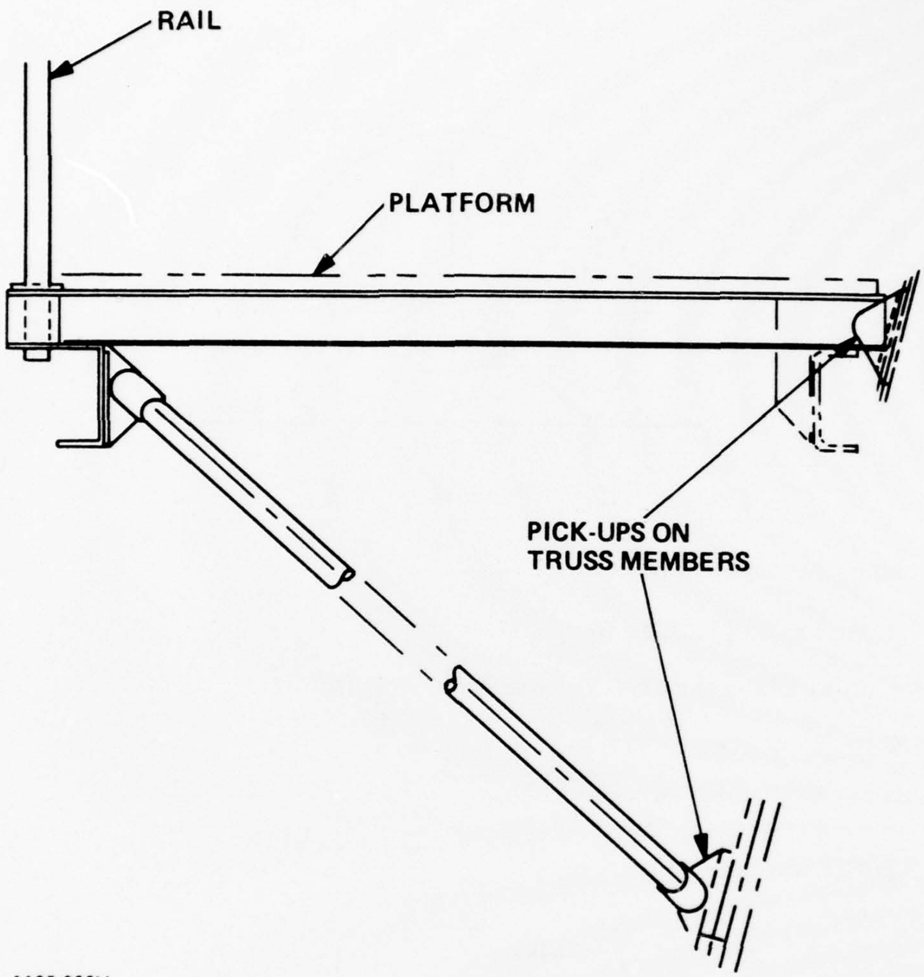


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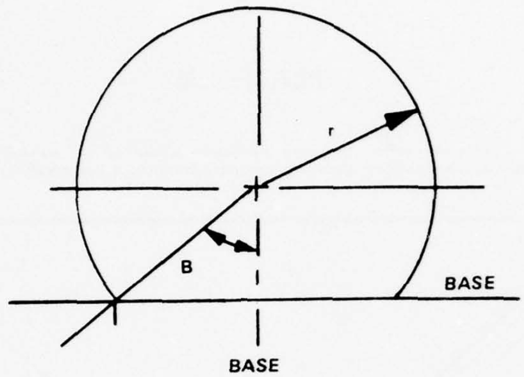
Figure 50. Typical Structure Workstand Section

ESTIMATED WEIGHTS

Estimated Weight of Dome Structure Translucent Dome



Surface Area above base

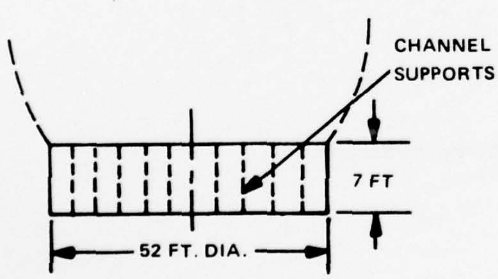
$$A = 2\pi r^2 (1 + \cos B)$$

For 68 Ft Diameter Dome of 5/8 thick Acrylic

Weight = $At\alpha$ = 49,642 lb

B = 40° α = .043 lb/in.^{3}

Base Support Structure



Using channels 4" x 1" x 3/16"

41 supports @ 7 ft long

2 circumf @ 164 ft long

Total channel length = 615 ft Total channel V = 4.8 cu ft

Side Wall V = 164 ft x 7 ft x 0.04 inches = 3.83 cu ft

Total Vol. of aluminum = 8.63 ft^3

Using wt/ft^3 of aluminum = 173 lb/ft^3

Total base support weight = 8.63 x 173 = 1520 lb

Lamp Support Truss Members - 80 Ft Dia

15 ft Sections

2 $in.^2$ CAPS @ 30 ft = 0.42 ft^3

0.3 $in.^2$ Ties @ 31 ft = 0.065 ft^3

Weight/Section = 0.485 ft^3 x 173 = 84 lb

It is estimated that approximately 195 sections would be used. Truss weight = 16,250 lb.

Ring members estimated at 1000 ft x 1.4 lb/ft = 1400 lb

Lamp Mounting Panels

Assuming Lamps occupy 55% of the total surface area and lamp mounting panels are 0.05 thick

$$Wt = \frac{45 \times 2 \pi r^2}{100} (1 + \cos B) \times \frac{0.05}{12} \times 173$$

$$= 5{,}360 \text{ lb}$$

Maintenance Workstand

Estimated weight/section = 100 lb. For 80 ft diameter Lamp Support Structure it is estimated to use 150 sections. Total weight for stands = 15,000 lb.

Summary of Weights

Transluscent Dome	50,000
Base Support Structure	1,500
Lamp Support Structure	23,000
Maintenance Stands	15,000
	89,500 lb

Conclusion

- Recommended Diffuser
  - Acrylic Self-Supporting Shell.
- Design Limitations
  - Max operating temp. 200°F
  - Max rate of surface temp. change 12°F/min.
- Interface requirements
  - Temperature control system
    - To limit maximum temperature
    - To control rate of change.

Recommended Testing Program

To establish a confidence level in the material properties and joint casting technique proposed and to provide necessary data essential to a final design effort the following testing program is required:

- Structural

  To ensure the structural integrity of the dome, the design mechanical properties of the material should be determined and the effect of temperature and time on these properties established.

As a minimum, the following properties should be determined for base material and cast joint:

- Tensile strength
- Modulus of elasticity
- Flexural strength
- Crazing threshold.

These properties are available for the more commonly used formulations of acrylic, but the custom nature of a resulting usable material and the cast joint technique for this program could have a significant effect on these properties.

- OPTICAL

  The uniformity of light transmission, diffusion and color achieved through the basic sheet and particularly at the cast joints should be investigated for different light intensities.

  The reflective properties of the inner surface for use as a reflective screen for image projection under varying light levels should also be investigated.

- ENVIRONMENTAL

  The conditions under which the system is operating will inevitably result in the build up of a static charge on the surface of the dome.

  To avoid the accumulation of dust and particles on this surface, which will degrade its function, methods of static discharge should also be investigated.

  Flushing the exterior surface with water is effective, but appears impractical.

  Coatings applied to the surface or anti-static compounds introduced at the sheet casting stage and in the joint casting resin would also be effective, but will have an impact on the mechanical and optical properties mentioned above and reinforces this requirement for data prior to detail design.

SECTION VIII
HEAT DISSIPATION

In order to establish the air conditioning requirements for the Crew Station Design Facility Feasibility Study (CSDFS) it was necessary to utilize the worst case ambient environmental conditions for the site of construction, Dayton, Ohio. The following defines the air conditioning design considerations used for the facility.

AIR CONDITIONING DESIGN REQUIREMENTS - WORST CASE

- Location
  - Dayton, Ohio
- Room dimensions
  - 100 FT X 100 FT
- Design ambient
  - Dry Bulb Temperature: $91^{o}F$
  - Wet Bulb Temperature: $73^{o}F$ (~55% RH).
- Lighting heat load
  - 2.5 megawatts
- Personnel heat load (assumed 50 men)
  - Sensible heat 3.66×10^{-3} megawatt
  - Latent heat 3.66×10^{-3} megawatt
- Internal ambient
  - $70^{o}F$ & 60% RH

It should be noted at this point that the variable of external make-up air used for this analysis was 10%. Therefore based on that factor the following ambient heat load is defined.

Heat Load Analysis Summary

- Ambient heat load
  - 2.9 megawatt
- Lighting heat load
  - 2.5 megawatt
- Personnel heat load
  - 7.32×10^{-3} megawatt
- Total heat load
  - 5.4 megawatts (1500 tons of refrigeration)

In order to meet the demands required for an internal ambient of $70^{\circ}F$ with a 60% RH the following Air Conditioning Components will be required:

Air Conditioning Components

- Water towers
  - 3 @ 500 tons each
- Chillers
  - 3 @ 500 tons each
  - SIZE
    L = 18' 6"
    W = 11' 3"
    H = 9'
- Power
  - 1106 kw (water pumps)
  - 1590 kw (chillers)
- Air handlers
  - 9 @ 60,000 cfm each
  - SIZE
    L = 10'
    W = 6'
    H = 12'
- Power:
  - 420 kw (fans)

To support this system water will be required as a sink for the air handlers and cooling towers. The pumping requirements and electrical service required for these components are defined as:

Water Pumping Requirements

- Air handlers
  - Water flow (total) = 200 gpm
  - Power = 32.2 kw
- Cooling tower
  - Water flow (total) = 41,100 gpm
  - Power = 1140 kw

Air Conditioning Power Requirements

The total definition of the electrical service required for the entire air conditioning system is:

• Chillers	1590
• Air handlers	
– Fans	420
– Water pumps	32
• Cooling tower	
– Water pumps	1074
TOTAL	3116

SKY SIMULATION LAMP SELECTION / DOME SURFACE TEMPERATURE ANALYSIS

Particular attention was given to the effect of the lamp configuration on the dome surface temperature. Selection of the lamp configuration is paramount in order to keep the dome surface below 200°F.

It was established that the OSRAM-1200 Watt "HMI" metal halide lamps could provide the required lighting for the CSDFS. (See Figure 51 for detailed design information.) Based on that conclusion and using the configuration definition for the the OSRAM-1200 W lamp, a thermal analysis was performed on a 68-foot dome. Since detailed information such as the lamp lens surface temperature is not available at this time, a gross bulk temperature calculation for the lamp housing assembly was determined for a 3 filter and no filter configuration. A free convection heat transfer coefficient of 0.5 BTU/FT^2 HR$^{\circ}$F with a boundary air temperature

Lamp (Ordering Abbreviation)	HMI 200 W	HMI 575 W	HMI 1200 W	HMI 2500 W	HMI 4000 W

OSRAM Metallogen® Lamps HMI

Power consumption of lamp P_L (W)	200	575	1200	2500	4000
Minimum supply voltage[1] $U_{O\,min}$ (V)	198 A.C.	198 A.C.	198 A.C.	209 A.C.	360 A.C.
Operating voltage U_L (V)	80	95	100	115	200
Current I_A (A)	3,1	7,0	13,8	25,6	24,0
Luminous flux Φ (lm)	16 000	49 000	110 000	240 000	410 000
Luminous efficiency lm/W	80	85	92	96	102
Nearest colour temperature approx. K	5600	5600	5600	5600	5600
Colour rendering index Ra	>90	>90	>90	>90	>90
Length l_1 max (mm)	75	145	220	355	405
Diameter d (mm)	14	21	27	30	38
Length l_2 max (mm)	60	115	180	290	340
Arc length (mm)	10	11	13	20	34
Average life (hrs.)	300	750	750	500	500
Burning position	horizontal ± 15°	any	any	horizontal ± 15°	horizontal ± 15°
Base	X 515 knife plug	sleeve with threaded pin M4	sleeve with threaded pin M6×0.5	SFa 21-12	SFa 21-12
Standard package (qty.)	10[2]	10[2]	10[2]	1	1
Price each					

[1] For operation with chokes only.
[2] Also available in individual package.

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Figure 51. HMI Lamp Specifications

surrounding the dome of 70°F was assumed. Because of the uncertainty of the lamp lens temperature, a Min/Max analysis was performed on the dome.

For the first case of the filter arrangement, the following was assumed:

(a) Three filters each with an IR transmissivity of 0.9

(b) Transmissivity of lamp lens of 0.9

(c) Light efficiency of lamp 95%

(d) 7% of lamp heat taken out by lamp leads to lamp housing

(e) Housing emissivity = 0.8

(f) Dome emissivity = 0.8

(g) Dome transmissivity = 0.7

Energy Balance on Housing

$$h_c A_c (T_a - T_H) + \sigma F_e F_a A_R (T_w^4 - T_H^4) + Q_H = 0$$

h_c = 0.5 Btu/ft^{2}hr°F

A_c = 52.89 ft^2 (housing convection surface area)

T_H = Housing temperature to be solved for

T_a = Ambient air temperature = 530°R

σ = .1714 X 10^{-8} Btu/ft^{2}hr°R^4

F_e = .8

F_a = 1

A_R = 14.14 ft^2 (housing radiation surface area)

T_w = Surrounding wall temperature = 530°R

Q_H = Heat lost to housing = 504 W = 1721 Btu/hr

For the above inputs, the housing temperature is 115°F.

Energy Balance on Dome

$$2h_c A_c (T_a - T_D) + \sigma\, FeFaA_R (T_H^{\,4} - T_D^{\,4}) + Q_D = 0$$

For this balance, it is assumed that the air temperature both inside and outside the dome is the same.

h_c = 0.5 Btu/ft^{2}hr°F

A_c = 10.56 ft^2

T_a = 530°R

T_H = 575°R

Fe = .8

Fa = 1

A_R = 10.56 ft^2

Q_D = Heat absorbed by dome = .3 (1200 - 504) = 209W = 712 Btu/hr

T_D = Dome temperature to be solved for

Based on the above inputs, the dome temperature was calculated to be 128°F.

The second case considered is the one in which no filters are used for the lamp. For that situation (Q_H = 140 W) and for the boundary conditions previously defined, the lamp housing temperature is 106°F. In as far as the dome is concerned, the heat absorbed is now Q_D = 318 W and the corresponding dome temperature is 138°F.

Since this type of analysis is based on a bulk housing temperature, it may tend to be optimistic with regard to dome temperature when one considers the actual lamp lens surface temperature in the final design analysis. However, for the configuration as defined, there appears to be sufficient thermal margin for the dome. The reason for this conclusion is that the free convection heat transfer coefficient for the profiles calculated is 0.8 Btu/ft^{2}hr°F instead of the 0.5 Btu/ft^2 hr°F assumed for the calculations. Using an average h_c of .65 Btu/ft^{2}hr°F, a dome temperature reduction of approximately 20°F would result.

SECTION IX
POWER SYSTEMS

POWER REQUIREMENTS

Study and estimate the total power requirement for the proper operation of the controlled ambient lighting environment test facility.

Discussion

The electric power requirements for the crew station design facility (CSDF) are summarized in Table 18. Efficiences were estimated for the power supplies/ conversion equipment and electric motors required by the various elements of the CSDF to arrive at a more comprehensive total power requirement. The monitor and control systems are the "housekeeping" elements of the CSDF and the power requirement is an estimated figure.

Figure 52 is a first cut attempt at a power distribution configuration for the CSDF installation. This configuration assumes the availability, at the CSDF site, of a 13.8 kv, 60 Hz power system with a 14 megawatt capacity. The 480V, 60 Hz equipment bus configuration is subject to change depending on the input voltage requirements of the equipment finally selected.

A preliminary review of available power equipment indicates a 2000 KVA secondary unit substation, (see Figure 53) which includes input and output switch gear and transformer section. Seven of these units would satisfy the facilities power requirements. The units are intended for indoor installation and are roughly 7 1/2' high by 16 1/2' wide by 5' deep. Each unit would require approximately 82 1/2 sq. ft. of floor space plus necessary work around area to allow maintenance of the units.

Table 18 CSDF Power Requirement Estimates

LIGHTING POWER:	INSTALLED LAMP PWR.	LAMP/PWR. SUP. EFF.	LINE PWR. RQD.
SKY SIMULATION			
• EXTERNAL SKY SIMULATION USING 1200 WATT METAL HALIDE LAMPS:			
- WHITE SKY (1420 LAMPS FULL DOME)	1700KW	75%	2270KW
USING 30KW XENON ARC LAMPS - CLOUD (26 LAMPS)	780KW	75%	1040KW
• "SKY" LIGHTING CONTROLS			200KW
SUN/MOON SIMULATION			
• TWO 30KW XENON LAMPS	60KW	75%	80KW
• "SUN" LIGHTING CONTROLS			20KW
TERRAIN SIMULATION			
• NOTE: POWER REQUIREMENT INCLUDED IN SKY SIMULATION; TERRAIN SIMULATION OBTAINED BY CONTROLLING AND FILTERING "SKY" LAMPS IN LOWER HEMISPHERE.			
		*LIGHTING POWER SUB-TOTAL:	3610KW

MOTION POWER:	INPUT PWR. TO HYD. DR.	ELECT. MOTOR/ CONT. EFF.	LINE PWR. RQD.
SUN MOVEMENT SIMULATION			
MOTION SIMULATION	6280KW	85%	7400KW
		MOTION POWER SUB-TOTAL:	7400KW

HEAT DISP./COOLING POWER:	LINE PWR. RQD.
HEAT DISSIPATION/COOLING	
• CHILLERS	1590KW
• AIR HANDLERS	452KW
• COOLING TOWERS	1074KW
HEAT DISP./COOLING POWER SUB-TOTAL:	3116KW

VISUAL/AUXILIARY POWER:	LINE PWR. RQD.
REDUCED VISIBILITY	15KW
VISUAL EFFECTS	5KW
MONITOR AND CONTROL SYSTEMS	50KW
VISUAL/AUXILIARY POWER SUB-TOTAL:	70KW
CSDF TOTAL POWER:	14.196MW

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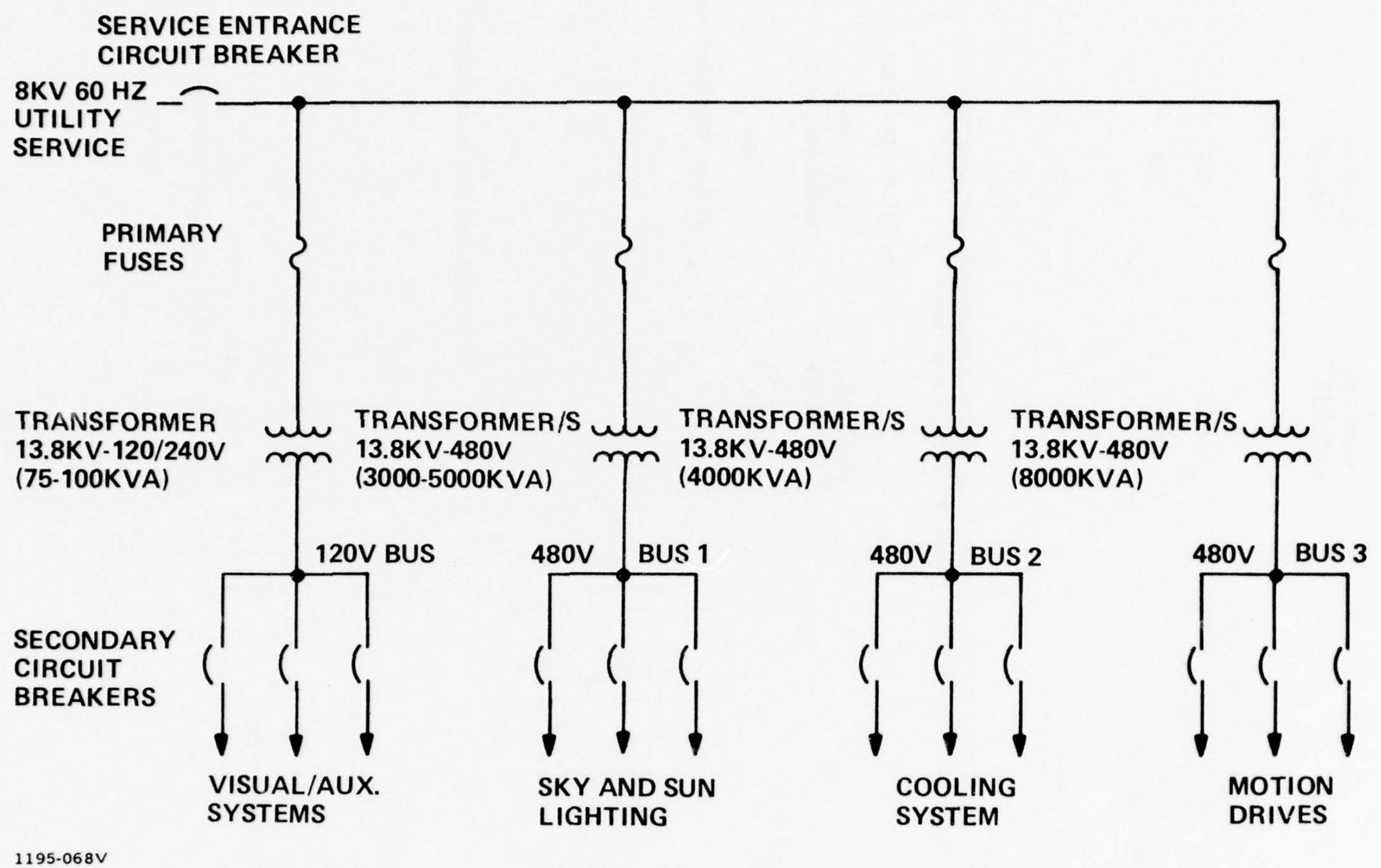

Figure 52. CSDFS Electric Power Distribution

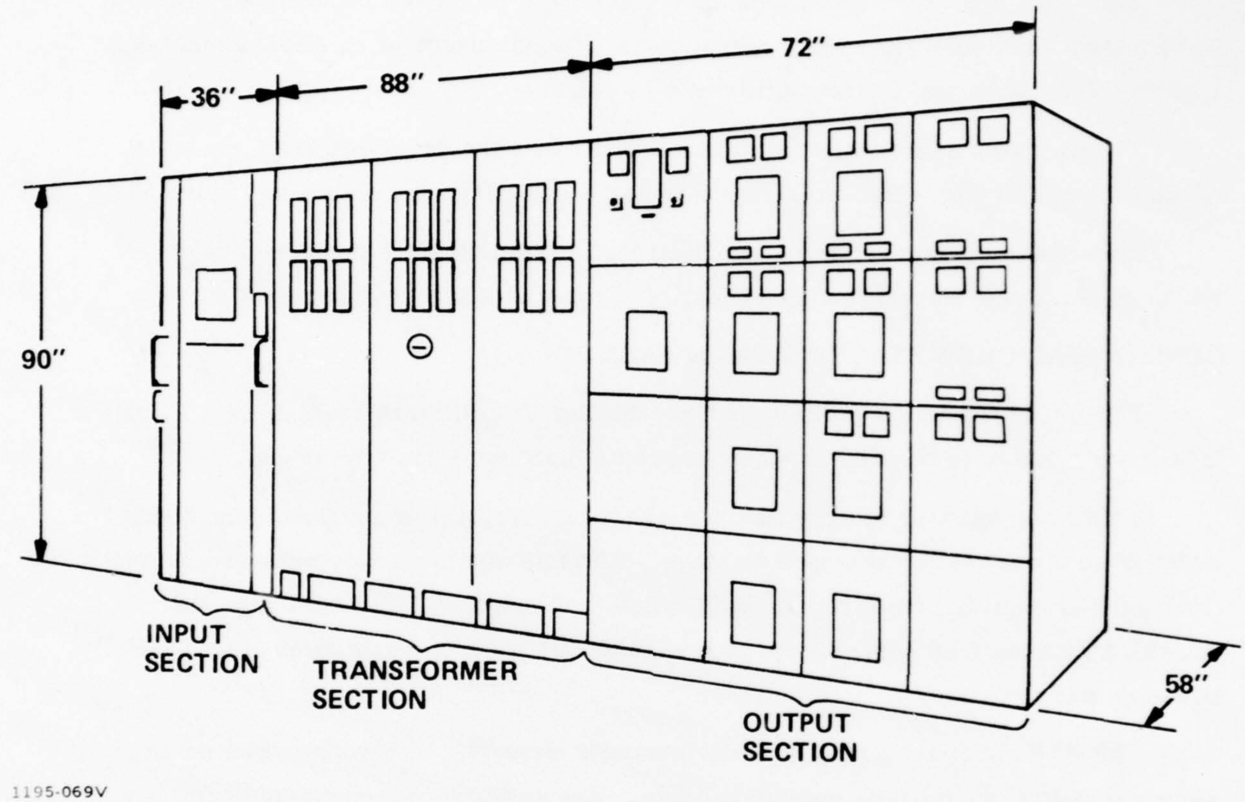

Figure 53. Secondary Unit Substation

SECTION X
SOFTWARE AND CONTROLS

INTRODUCTION

This software overview addresses the software functional capabilities that may be required for the development, operation, and maintenance of an Environmental Lighting Simulation and the feasibility of this software.

The operational software functional capabilities are developed from analysis of the Conceptual Crew Station Design Facility Block Diagram, shown in Figure 54.

Experimentor support software functional capabilities are developed from analysis of a Crew Station Design Facility Operational Concept shown in Figure 55.

CONCEPTUAL CREW STATION DESIGN FACILITY

Figure 54 depicts a conceptual Crew Station Facility that consists of a Flight Mission Simulator (FMS) and an Environmental Lighting Simulator (ELS).

FMS is an existing facility that consists of a computer and a fixed base cockpit which contains flight controls and displays. The mission simulator software provides the required stimulus for aircraft flight mission simulation. The computer will interface with the ELS computer to provide aircraft position input data to the ELS software math models.

The ELS consists of artificial environment elements, controller, computer, software, and experimenter control console. The artificial environment hardware provides simulated:

- Sky
- Sun/Moon
- Horizon
- Visual effects generators (clouds, haze, snow, rain)

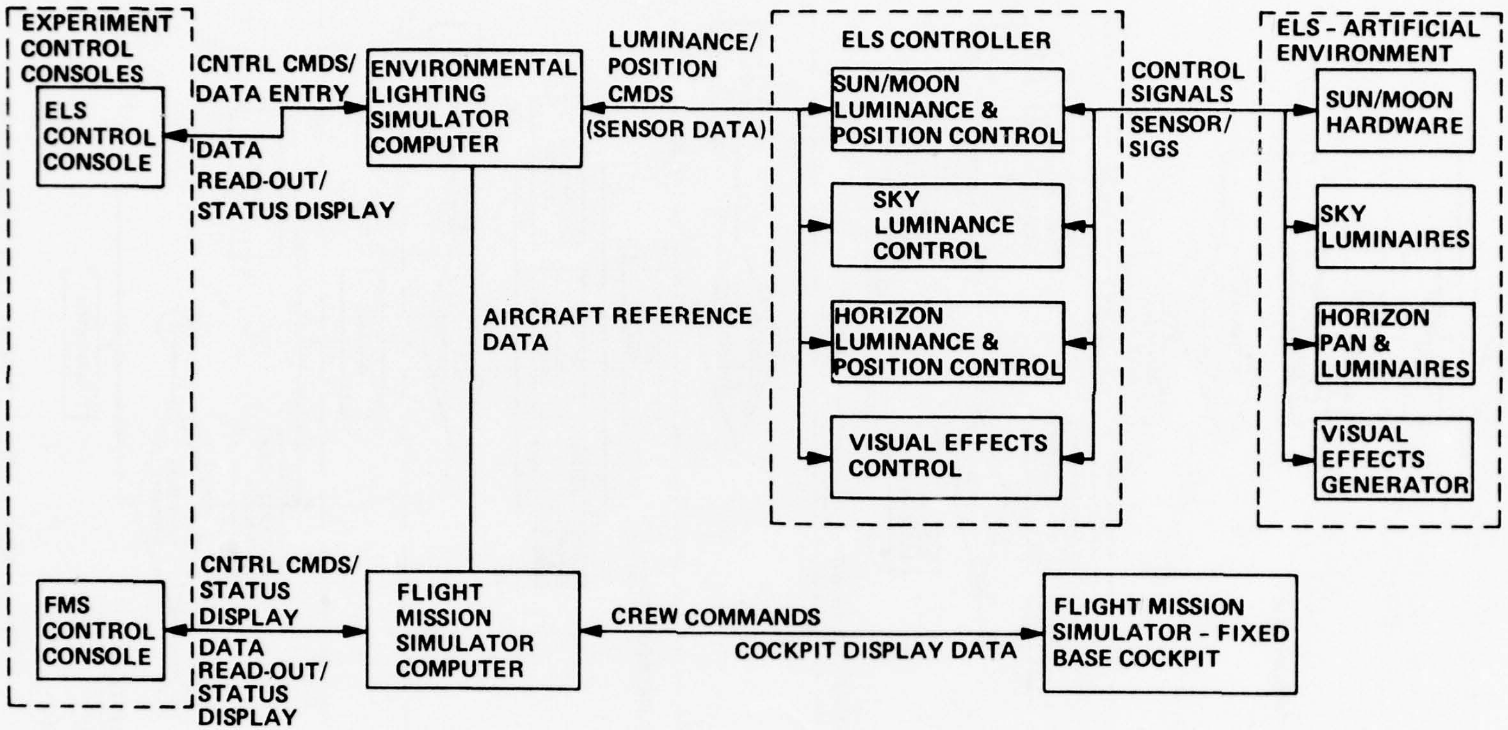

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Figure 54. Crew Station Design Facility Functional Block Diagram (Conceptual)

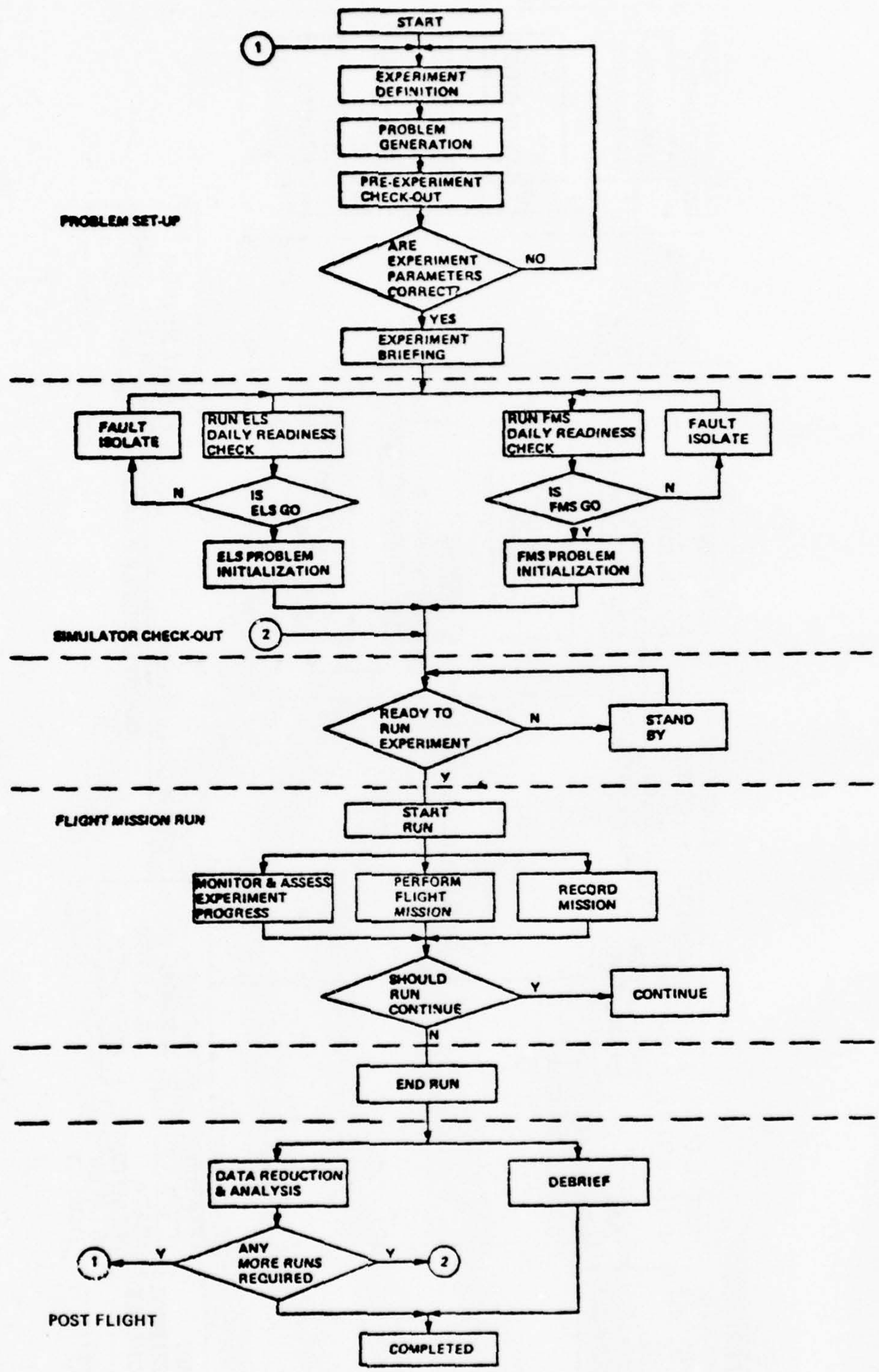

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Figure 55. Crew Station Design Facility – Operational

The controller drives the artificial environment in response to commands generated by the ELS Math Models.

These models reside in the ELS computer which also supports the other essential software functions to control the ELS. These functions included are:

- Real time executive
- Input/output controller and handlers
- Environmental lighting math models (sun/moon, clear sky, clouds, fog, haze, rain, snow)
- Environmental lighting sensors data processing
- Mission recording
- Display

The overall ELS functional software is described below. The experiment control console contains the controls and displays that will allow the experimentor to monitor and interact with the ELS.

CREW STATION DESIGN FACILITY OPERATIONAL CONCEPT

Crew Station Design Facility Operations can be characterized in terms of four operational phases:

- Problem set up
- Simulation checkout and initialization
- Flight mission run
- Post-flight analysis

The activities associated with each phase and the interrelationship between the phases are summarized in the operational flow chart of Figure 55.

During the set-up phase, the crew station design and human factors personnel would formulate the problem to be evaluated and determine the applicable parametric values for the aircraft and environment lighting system math models. These values would be entered into the environment lighting system computers through the experimentor control console. Both FMS and ELS would be run through some check points to verify that experiment test conditions are correct.

The simulators are checked to assure the operational state of readiness.

The post flight analysis phase includes data reduction and analysis to establish the need for additional experiment runs. Minimum turn around time is mandatory.

Experiment support software would be required for:

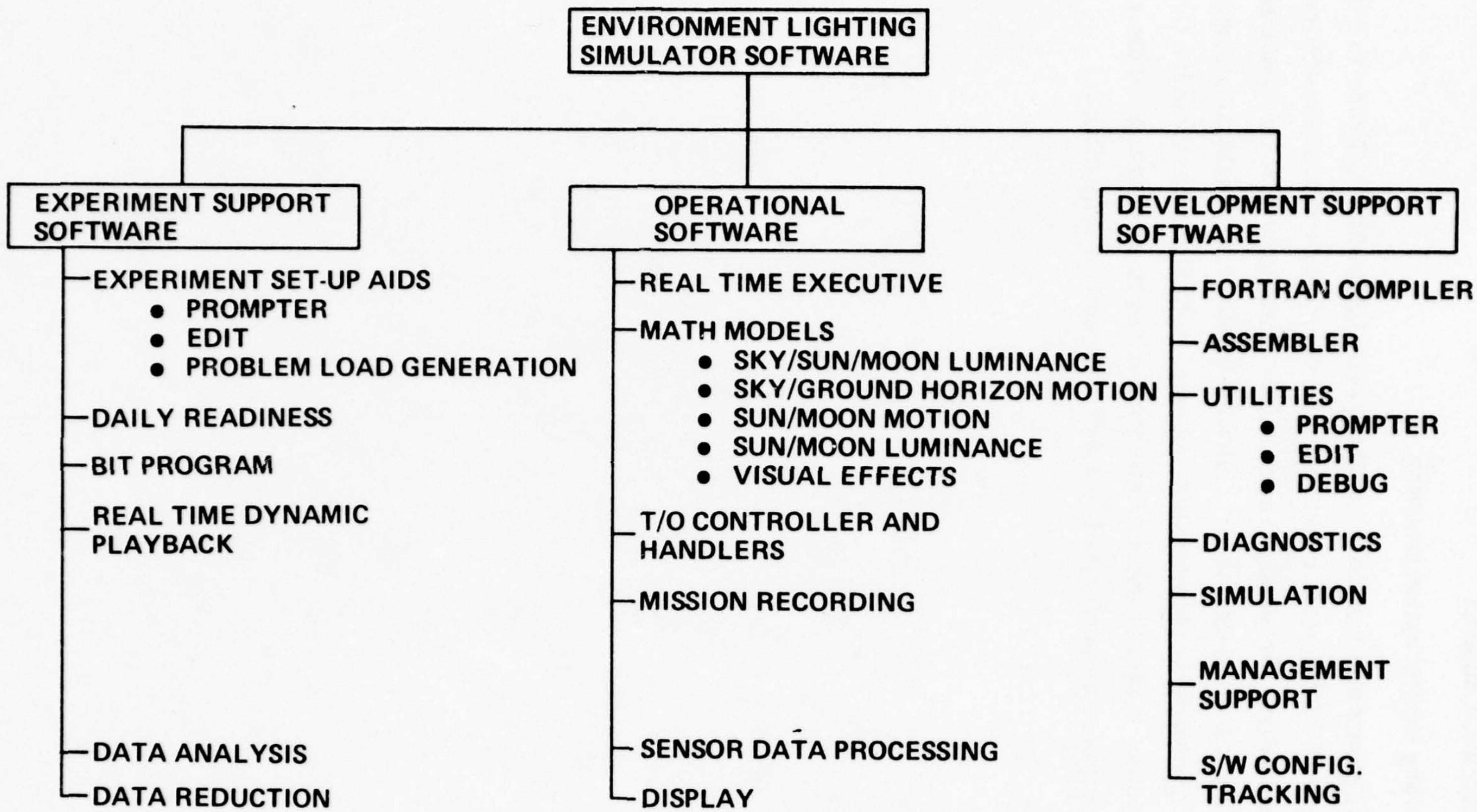
- Experiment interface
- Generation of problem
- Daily readiness checkout
- Data reduction
- Data analysis

ENVIRONMENTAL LIGHTING SIMULATOR SOFTWARE FUNCTIONAL CAPABILITIES

An overview of the functional software required for the ELS operation, experiment support and software development is shown in Figure 56. An additional set of development support software is required to permit the orderly and logical development of the operational and experiment support software.

This development support software provides the capability for "building", testing, integrating, tracking, and managing the software developmental process. This software includes:

- Fortran compiler
- Assembler
- Utilities
- Diagnostics
- Simulation



1195-072V

Fig. 56 Environmental Lighting Simulator Software Functional Configuration

- Management Support
- Software configuration tracking

The range, extent and feasibility of the total ELS system software is dependent upon the definition of ELS system requirements, the hardware implementation scheme and hardware limitation. Presently, there exists little doubt that the required software is well within the state-of-the-art. However, an overly ambitious system specification or hardware implementation scheme could significantly drive the software development costs. Essential analysis of requirements and hardware/software tradeoffs must be performed to assure the software feasibility.

SECTION XI

RECOMMENDATIONS FOR FURTHER STUDY

The successful implementation of an externally illuminated translucent dome can be assured by development of the following materials, techniques, and equipment.

TRANSLUCENT DOME MATERIAL

The best combination of translucence, transmittance, reflectance, and reflective gain should be determined by a fabrication and test program. The program should determine the ability to achieve the reflective gain by lenticularizing the inner surface and achieving the reflectance and diffusivity by whatever means are most practical.

The ability to bond the material edge to edge without a visible seam must be demonstrated.

DIFFUSE DOME LUMINAIRE

The efficiency of a diffuse luminaire should be measured full scale and provisions for locating the lamp, mechanical intensity control, and color control filters evaluated.

The ability to create uniform luminance variation by controlling the distance between the luminaire and the dome should be demonstrated.

The ability to control sky color in the presence of cloud simulation should be confirmed.

The ability to provide the desired range of color and spatial control of color should be demonstrated.

TERRAIN SIMULATION

A range of paints/pigments should be identified and demonstrated (minus blue and minus red) for use on the terrain pan to control the transmittances of light from the dome. They should provide a range of realistic terrain hues.

SOLAR SIMULATOR

A preliminary design of a solar simulator should be performed to achieve the simulation requirements with a minimum moment of inertia and minimal increase in the dome radius (above 20 feet).

MOVING BASE SIMULATOR

The use of a fixed base cockpit increases the number of lamps required for sky simulation in the CSDF and requires the terrain pan and the sun to rotate at high velocities with respect to the cockpit. The moment of inertia of the terrain pan with the solar arm attached is unfavorable; very large torques are required to simulate aircraft angular motion. The technical problems associated with simulating motion convinced the study team that it would be advantageous to investigate the use of the translucent dome with a moving base cockpit. Although it was beyond the scope of the Statement of Work to study this approach, its advantages became more evident as the design complications associated with the fixed base cockpit configuration were assessed and tabulated.

APPENDIX A

SKY AND TERRAIN

MEASUREMENTS DATA

BY THE

VISIBILITY LABORATORY

UNIVERSITY OF CALIFORNIA

SAN DIEGO

APPENDIX A

INTRODUCTION

The enclosed data were measured by the Visibility Laboratory, under contract with the Air Force Geophysics Laboratory. The principal task of this ongoing program is to take daytime and nighttime atmospheric optical measurements and, from these measurements, to determine optical properties for various paths of sight.

The measured properties include total volume scattering coefficients, sky, sun, and terrain radiances, upwelling and downwelling irradiances, horizon radiances, path functions, temperatures, dewpoint temperatures, and pressures. The computed properties are determined from the scattering coefficients and the sky and terrain radiances. The other measurements are utilized mainly as an independent cross check of the computed properties including the natural irradiances upon horizontal plane surfaces, scalar irradiances, atmospheric beam transmittances, directional terrain reflectances, path functions, equilibrium radiances, path radiances, and directional path reflectances.

The above terms are defined in Duntley (1975). The data may be used for a variety of real-world visibility applications, as well as theoretical applications such as evaluation of models. The measurements have been taken in a variety of meteorological and optical conditions, in various geographical areas. The measurements are normally taken in three to four spectral bands in the visible, plus one near infra-red spectral band.

The listed references discuss instrumentation and related topics in detail, and present some of the above properties on a number of flights.

The enclosed data are the measured sky radiances in radiometric units at two altitudes, on each of four flights. A summary table of the data is given in foot lamberts. The following sections include a description of the data measurement techniques, the computations, and the flight conditions for the enclosed data.

DATA MEASUREMENT TECHNIQUES

The sky radiances were measured by a radiometer mounted on a C-130 aircraft. Radiance is basically the radiant power per unit area per unit solid angle in a given direction. The radiometer is designated the Automatic 2 Scanner Assembly, or Upper Hemisphere Scanner. It consists of a multiplier phototube assembly, temperature control housing assembly, optical filter assembly, radiometer measuring circuit assembly, and optical collector assembly.

The optical collector assembly is essentially a small telescope that can be directed to scan any point within a 2 steradian field of view. The telescope itself has a circular field of view with an angular diameter of 5 degrees. The scanner is directed in a sweep pattern which covers the full hemisphere in 180 seconds. Starting near the horizon, the scanner makes a revolution around the horizon to measure radiances at the zenith angle 87.5°, for azimuth angles 0 to 360°. Each following revolution is 5° higher in elevation (5° less in zenith angle). The hemisphere is scanned in a total of 18 revolutions.

On a clear day, the data near the sun are normally offscale bright. For this reason, a calibrated 3 log neutral density filter is inserted in the optical path, and an additional upper hemisphere scan is recorded. The two data sets are referred to as the sky mode and sun mode data.

During the sky radiance data taking, the aircraft flies at a constant altitude with a constant heading and flight attitude. Although these patterns are referred to as a "straight and level," the pattern is normally flown with a 2.5° aircraft pitch angle. The data are normally recorded in four spectral bands at four altitudes between 500 and 20,000 feet.

The available spectral bands are illustrated in Figure A-1. The data presented here were taken with filter 4, the pseudo-photopic, which approximates the photopic response of the human eye.

The radiometer was calibrated using standard photometric practices with a 3-meter optical bench and incandescent standards of luminous intensity traceable to the National Bureau of Standards. The radiances are presented in the units watts per steradian per meter squared per micro meter of spectral bandwidth, that is, watts/SR m^2 m. The data may be converted to the luminance units foot-lamberts by multiplying by 21.0. This factor properly accounts for the change in units and for the different spectral sensitivities of the instrument and of the light-adapted human eye (i.e., photopic sensitivity).

DERIVATION AND PRESENTATION FORMAT OF ENCLOSED DATA

This section discusses the derivation and meaning of the parameters which are tabulated and graphed. The nomenclature used in the tables and graphs is discussed in a later section.

Sky and Terrain Radiance Tables

The sky and terrain radiance tables represent a portion of the radiances measured by the Upper and Lower Hemisphere Scanners. Values are presented for each 5° in zenith angle between 2.5° (near the zenith) and 177.5° (near the nadir). Only data in the four cardinal azimuths $= 0^{\circ}$, 90°, 180°, and 270° relative to the sun are presented. An additional table which includes the data at every 6° in azimuth angle is available on most flights, but has not been included here.

Note that the radiances on the graph are the radiances averaged out over the 5° field of view of the radiometer. When the actual radiance is not constant over the field of view of the photometer, these data must be interpreted with caution. In particular, the sun radiance as measured with a 5° field of view is quite different from the true sun radiance which would be measured by a radiometer with a field of view smaller than the sun.

Although the data are sorted by azimuth relative to the sun, the azimuth angles are not exact, due primarily to variations in the relative heading of the aircraft during the data taking. Therefore, the data at $= 0$ may or may not include a point in which the sun was actually in the field of view of the photometer. More accurate displays at the measured sky radiances near the sun are available but not included here.

As noted in the previous section, upper hemisphere data are in two modes, sky mode and sun mode. The enclosed data were recorded in sky mode. For this reason the data near the sun may be offscale bright. Offscale bright values are tabulated with the exponential value 10^{22} (or E 22 in computer notation).

The data have not been edited, and may include spurious points. In particular, the scanner path of sight includes portions of the aircraft such as the tail, in a few directions. Deletion of these point occurs in a later stage of the processing.

Sky and Terrain Radiance Graphs

These data are graphed as a function of zenith angle. There are four curves, one for each cardinal azimuth. In cases where the scale of the graph goes beyond the calibrated range of the instruments, the maximum or minimum calibrated values are noted by straight lines labeled ZSV and MCV, respectively.

Summary Table

The range of values appropriate to the zenith, the horizon away from the sun, and the nadir, are presented in the summary table, in foot-lamberts. The zenith and nadir ranges are the maximum and minimum values from the data at zenith angles 2.5° and 7.5°, and at 172.5° and 177.5°. The range for the horizon sky is determined by the maximum and minimum values in the cross-sun and down-sun directions at zenith angles 82.5° and 87.5°. The data have been converted to foot-lamberts by multiplying by 21.0.

FLIGHT DESCRIPTION AND SPECIAL CONSIDERATIONS

Flight C-360B 28 July 1974

This morning flight occurred near Rainier, Washington. The flight was conducted over flat grassy prairie surrounded by thick pine woods. The sky was clear.

On this flight, data were recorded in the pseudo-photopic filter only. Two data sets, recorded at 1143 and 500 meters above ground level, (AGL) have been included.

It should be noted that the azimuth angles on the high altitude data set are in error by 12°. Also, the measured aircraft altitudes are 180 meters too high on both sets. Both of these problems are a result of an electrical problem on the aircraft.

Flight C-354 16 July 1974

This morning flight occurred near Rainier, Washington. The flight was conducted over flat grassy prairie surrounded by thick pine woods. The sky was overcast.

On this flight, data were recorded in the pseudo-photopic filter only. Two data sets, recorded at 1116 and 549 meters, AGL, have been included.

It should be noted that the measured aircraft altitudes are 180 meters too high, as a result of an electrical problem on the aircraft.

Flight C-151 24 October 1970

This morning flight occurred near Socorro, New Mexico. The flight was conducted over a desert valley. The sky was clear.

Data were recorded in the blue, pseudo-photopic, and red filters. The data presented here are pseudo-photopic data measured at 4422 and 726 meters AGL. At the time these data were collected, the pseudo-photopic filter was labeled Filter 5.

Flight C-289 14 June 1973

This afternoon flight occurred in Northern Germany. The flight was conducted over low-lying flat terrain consisting mainly of cultivated farmlands interspersed with dark patches of dense woods. The sky was sunlit, with a broken layer of clouds.

On this flight data were recorded in the blue, photopic, red, and near infra-red filters. The data presented here are pseudo-photopic data measured at 1192 and 258 meters AGL.

The azimuth angles are in error by $6\text{-}12^{\circ}$, as a result of an electrical problem on the aircraft.

NOMENCLATURE USED ON TABLES AND GRAPHS

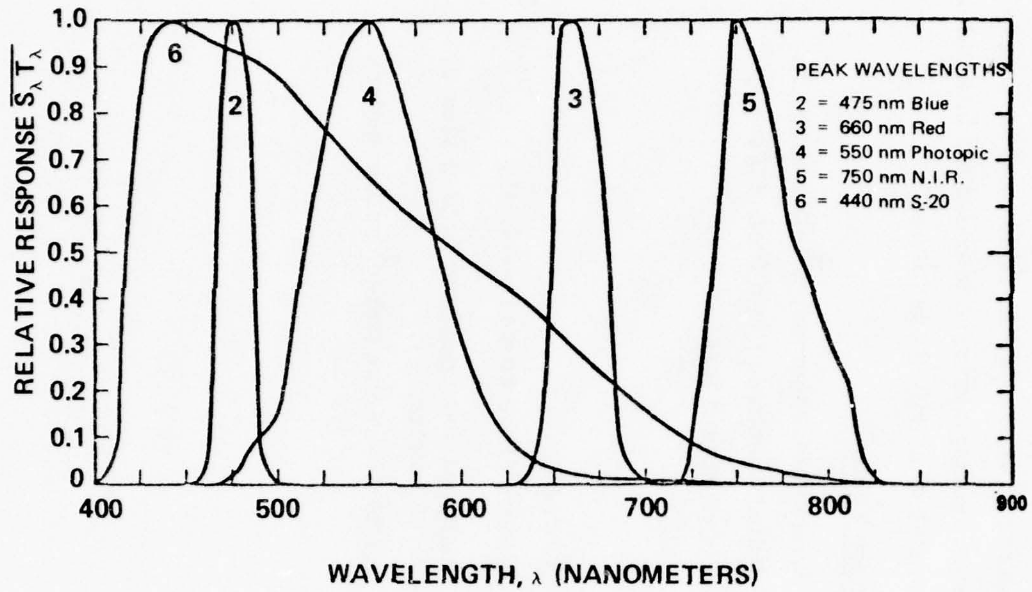
Some of the terms used to identify the tables and the graphs are not completely self-explanatory because the displays were intended for internal use only. The following listing is intended to clarify those terms:

Sky and Terrain Radiance Table

W/SR SQ M UM	Watts/(steradian meter^2 micro-meter).
Filter 4 or 5	Pseudo-photopic filter (Ref. Figure 1).
AGL	Above ground level.

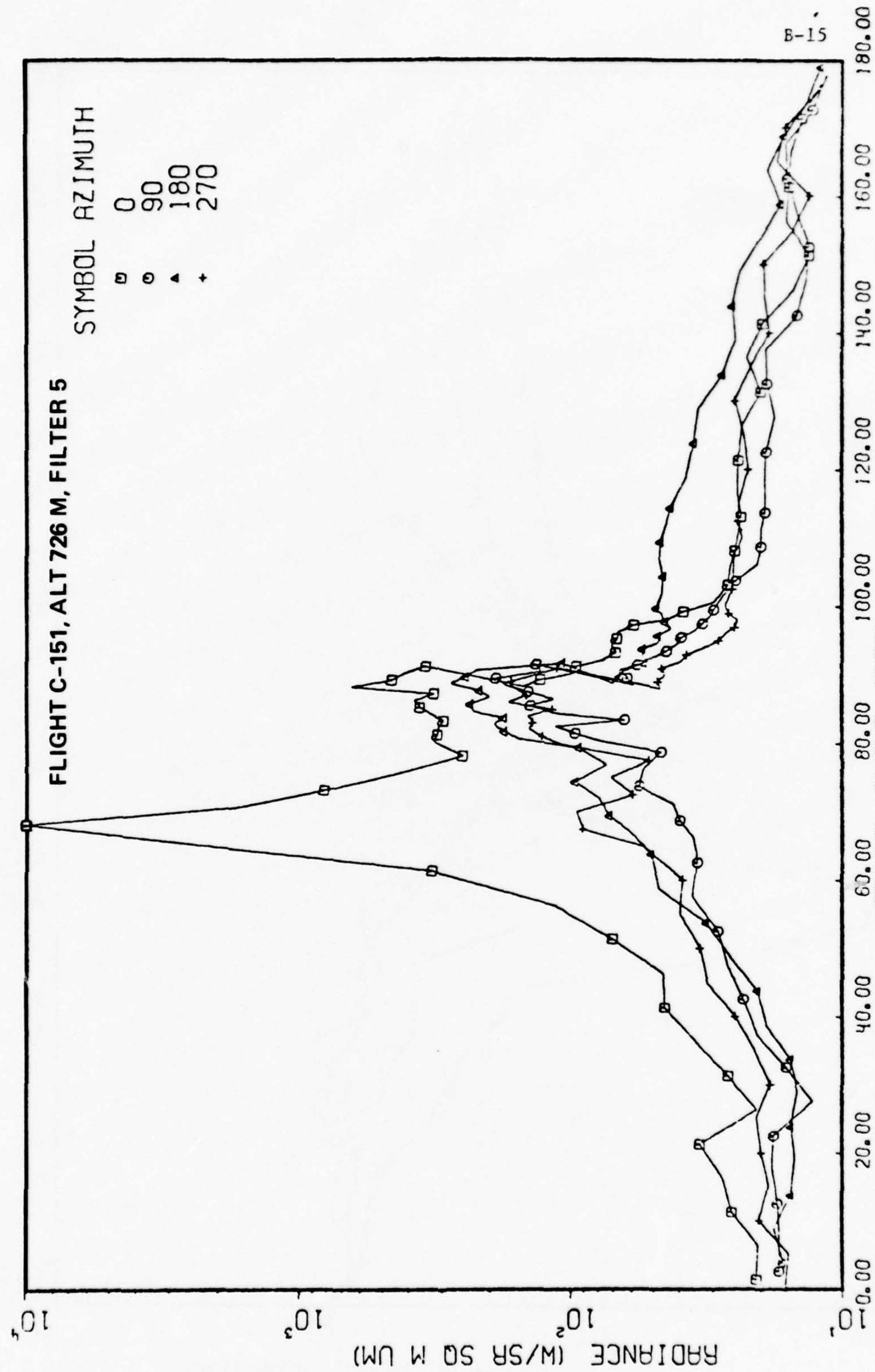
Graph

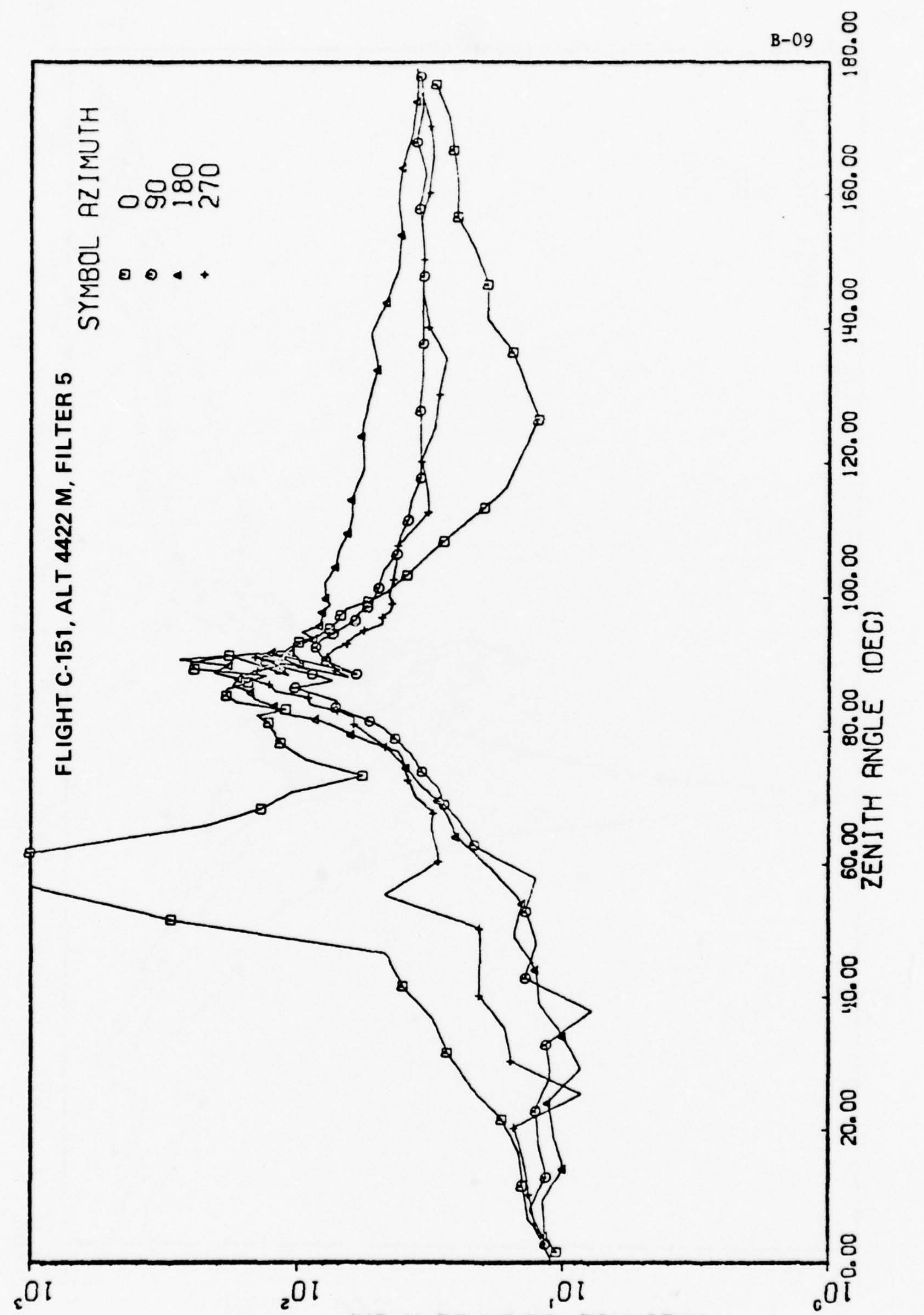
ALT	Altitude
(M) AGL	Meters above ground level.
Radiance	Radiance averaged over field of view of radiometer.
W/SR SQ M UM	Watts/(steradian meter^2 micro-meter).



1195-074V

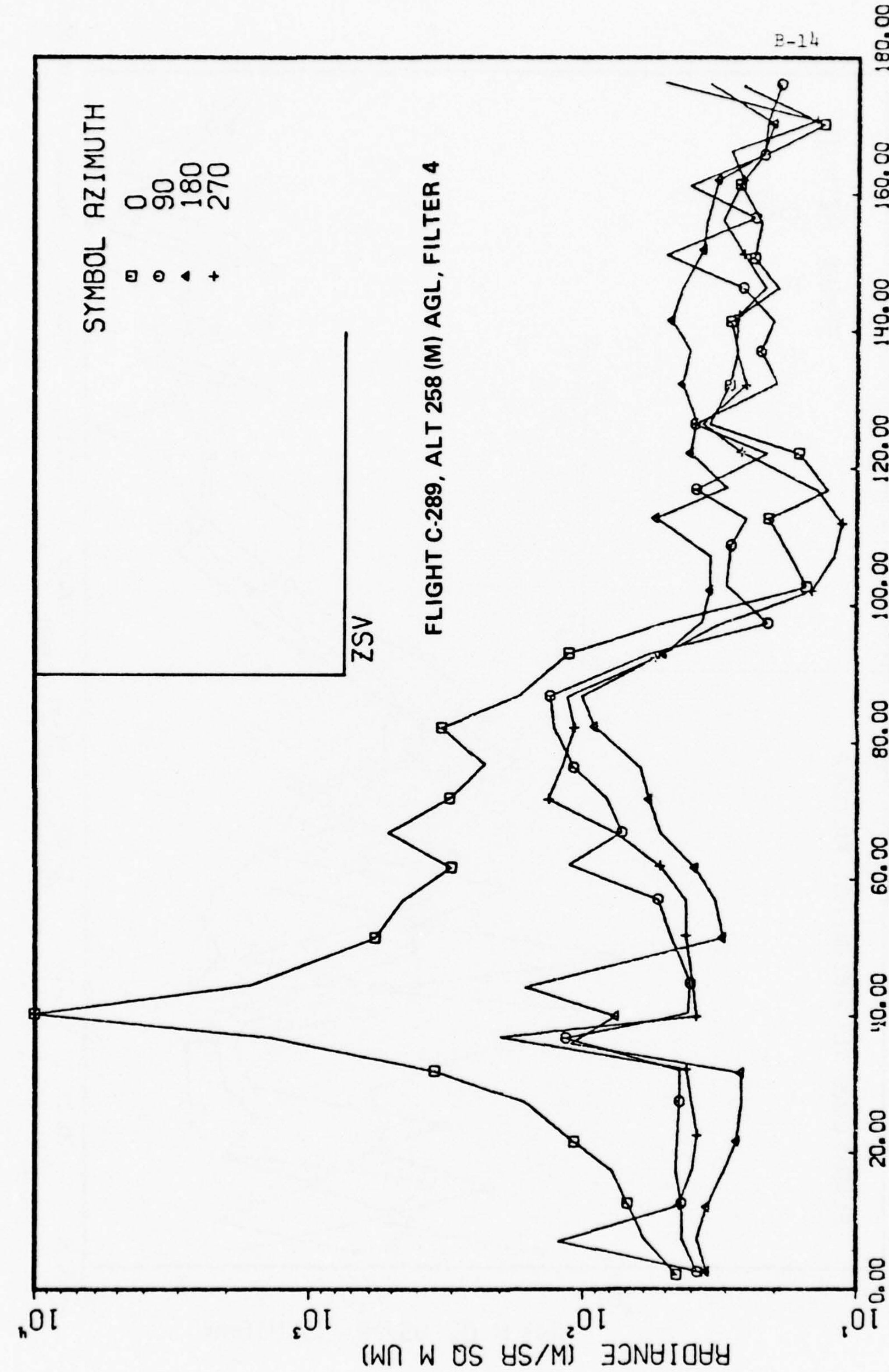
Figure A-1 Standard Spectral Responses


B-15
FLIGHT C-151, ALT 726 M, FILTER 5
SYMBOL AZIMUTH
0
90
180
270
RADIANCE (W/SR SQ M UM)
10^4
10^3
10^2
10^1
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
ZENITH ANGLE (DEG)
0158-080P

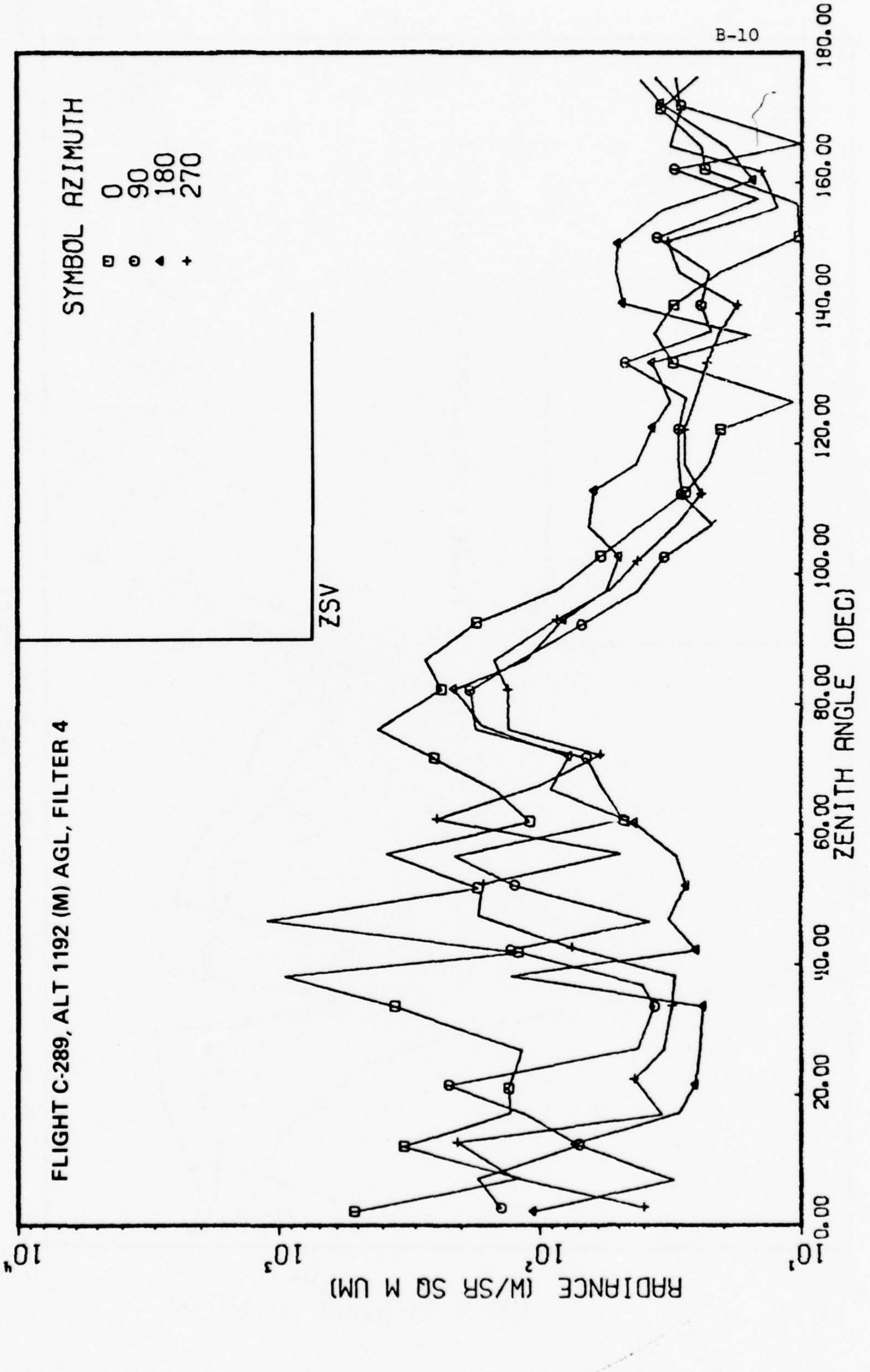


B-09
FLIGHT C-151, ALT 4422 M, FILTER 5
SYMBOL AZIMUTH
0
90
180
270
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
ZENITH ANGLE (DEG)
10^0
10^1
10^2
10^3
RADIANCE (W/SR SQ M UM)

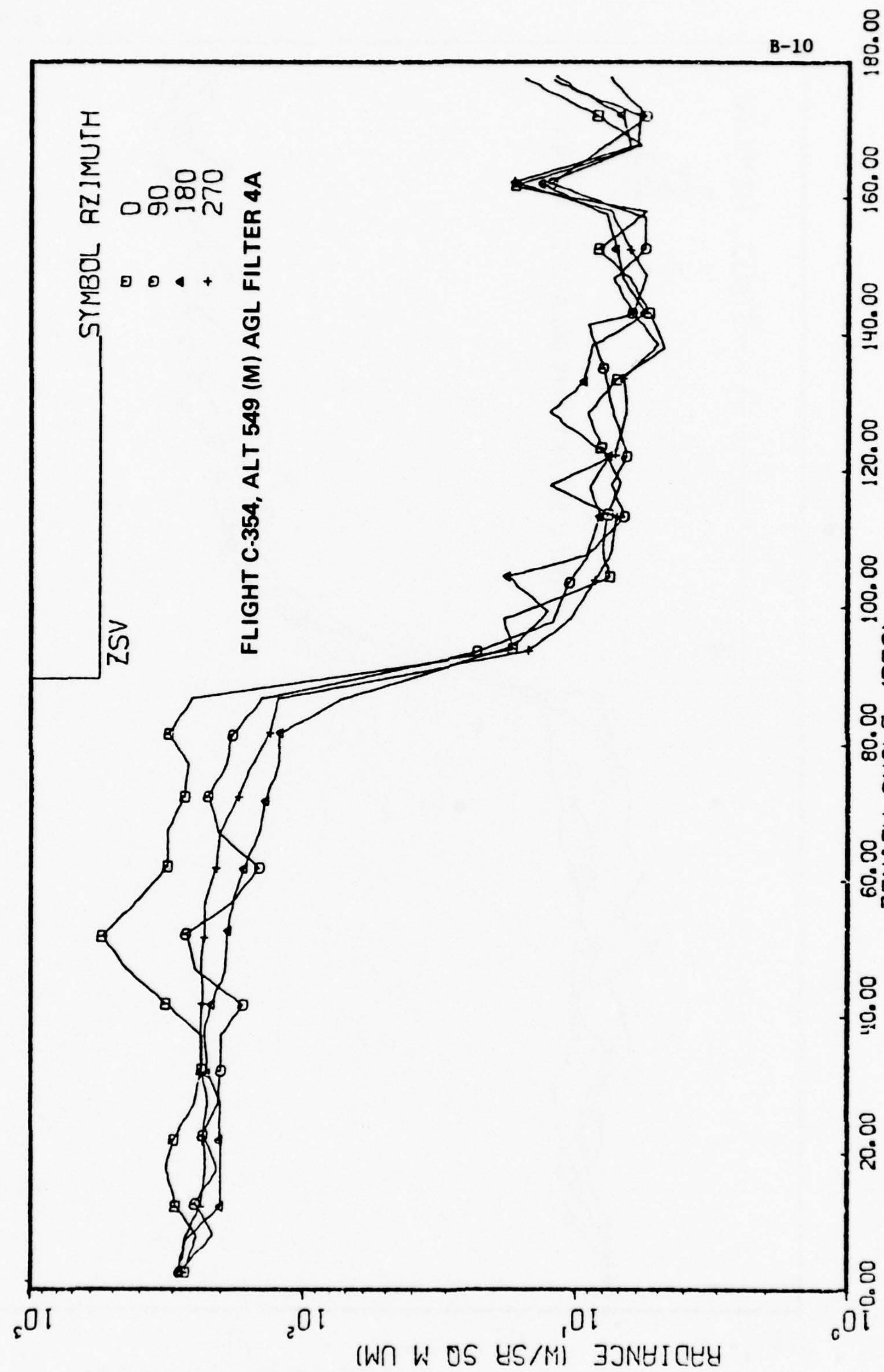
0158-079P



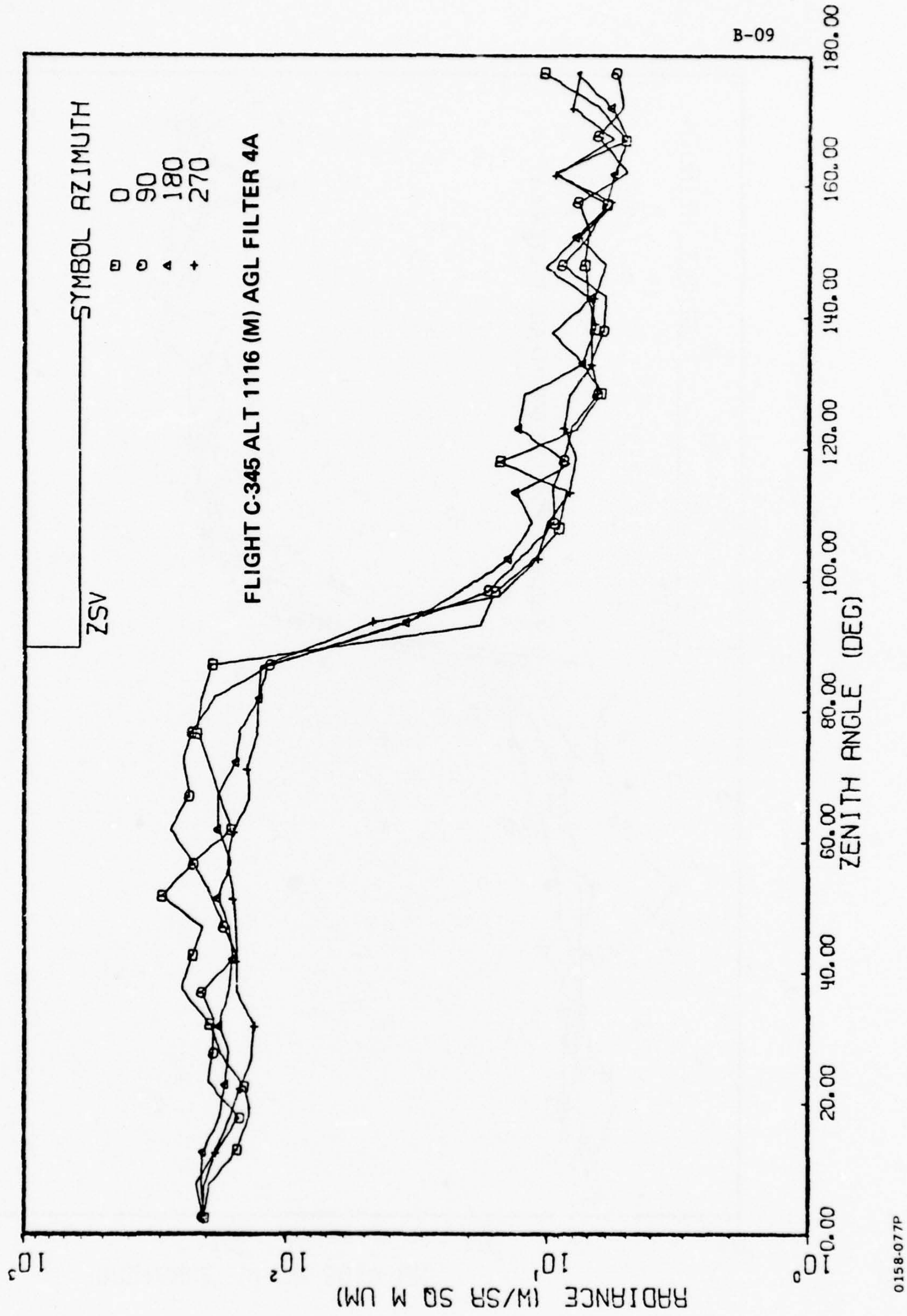
B-14
SYMBOL AZIMUTH
0
90
180
270
FLIGHT C-289, ALT 258 (M) AGL, FILTER 4
ZSV
RADIANCE (W/SR SQ M UM)
10⁴
10³
10²
10¹
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
ZENITH ANGLE (DEG)
0158-082P

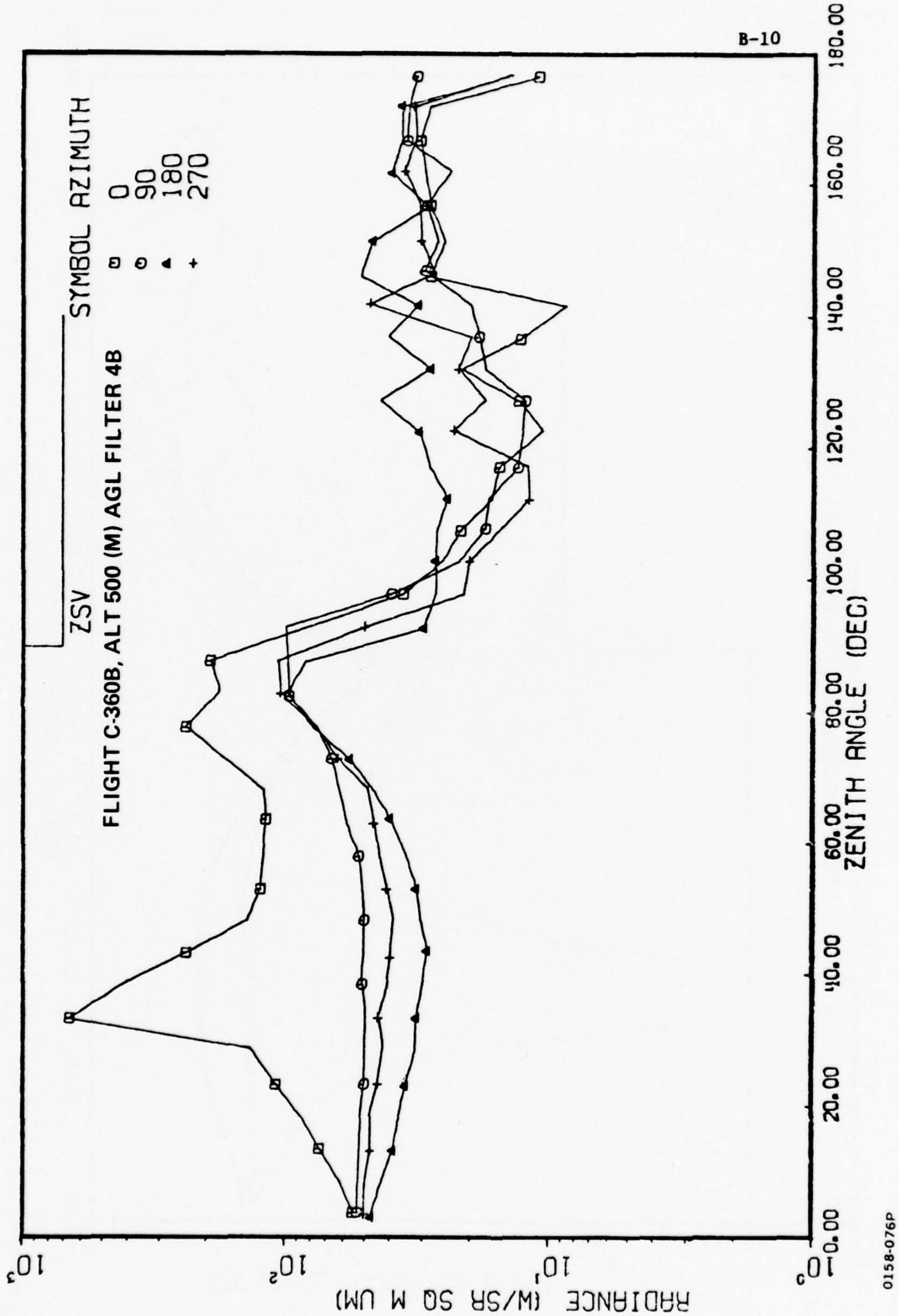

FLIGHT C-289, ALT 1192 (M) AGL, FILTER 4
B-10
SYMBOL AZIMUTH
0
90
180
270
ZSV
RADIANCE (W/SR SQ M UM)
10^4
10^3
10^2
10^1
ZENITH ANGLE (DEG)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00

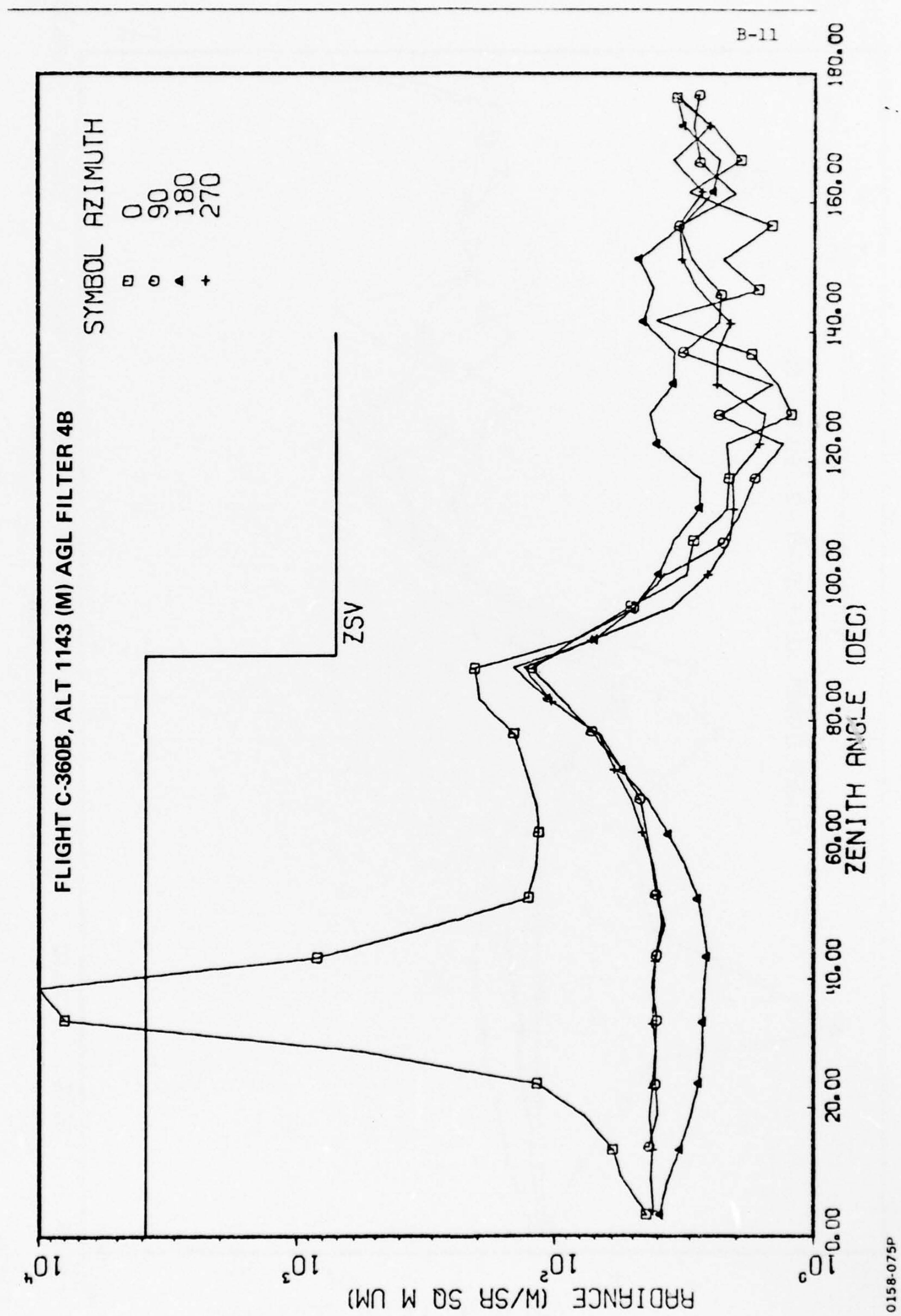
0158-081P



B-10
FLIGHT C-354, ALT 549 (M) AGL FILTER 4A
SYMBOL AZIMUTH
0
90
180
270
ZSV
ZENITH ANGLE (DEG)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
RADIANCE (W/SR SQ M UM)
10^0
10^1
10^2
10^3
0158-078P


B-09
FLIGHT C-345 ALT 1116 (M) AGL FILTER 4A
SYMBOL AZIMUTH
0
90
180
270
ZSV
ZENITH ANGLE (DEG)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
RADIANCE (W/SR SQ M UM)
10^0
10^1
10^2
10^3
0158-077P


B-10
FLIGHT C-360B, ALT 500 (M) AGL FILTER 4B
ZSV
SYMBOL AZIMUTH
0
90
180
270
RADIANCE (W/SR SQ M UM)
10^3
10^2
10^1
10^0
ZENITH ANGLE (DEG)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
0158-076P


B-11
FLIGHT C-360B, ALT 1143 (M) AGL FILTER 4B
SYMBOL AZIMUTH
0
90
180
270
ZSV
RADIANCE (W/SR SQ M UM)
10^0
10^2
10^3
10^4
ZENITH ANGLE (DEG)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
0158-075P

FLIGHT C-151

GROUND LEVEL ALTITUDE
1448 M

SKY AND TERRAIN RADIANCES (W/SR SQ M UM)

FILTER 5
55.3 SOURCE ZENITH ANGLE
4422 M ALTITUDE (AGL)

AZIMUTH

.9	90.9	180.9	270.9
1.05E 01	1.16E 01	1.17E 01	1.11E 01
1.36E 01	1.33E 01	1.19E 01	1.27E 01
1.42E 01	1.16E 01	9.95E 00	1.34E 01
1.47E 01	1.24E 01	1.09E 01	1.41E 01
1.70E 01	1.26E 01	1.13E 01	1.53E 01
2.24E 01	1.11E 01	8.60E 00	8.45E 00
2.74E 01	1.15E 01	9.98E 00	1.57E 01
3.09E 01	7.76E 00	1.23E 01	1.66E 01
4.00E 01	1.37E 01	1.26E 01	2.06E 01
4.67E 01	1.26E 01	1.53E 01	2.04E 01
2.98E 02	1.37E 01	1.42E 01	2.06E 01
4.94E 22	1.26E 01	1.83E 01	4.67E 01
1.10E 03	2.16E 01	2.52E 01	2.91E 01
1.36E 02	2.46E 01	2.70E 01	3.06E 01
5.65E 01	2.95E 01	3.46E 01	3.81E 01
1.16E 02	3.70E 01	4.16E 01	4.62E 01
1.42E 02	6.32E 01	1.16E 02	6.14E 01
1.53E 02	7.36E 01	1.65E 02	1.27E 02

AZIMUTH

2.4	92.4	182.4	272.4
1.08E 02	8.50E 01	1.02E 02	7.33E 01
6.89E 01	5.88E 01	8.04E 01	4.78E 01
3.87E 01	4.95E 01	7.89E 01	4.34E 01
2.80E 01	4.22E 01	6.94E 01	4.17E 01
1.96E 01	3.84E 01	6.22E 01	3.21E 01
1.62E 01	3.44E 01	5.60E 01	3.24E 01
0	3.42E 01	5.73E 01	3.41E 01
1.24E 01	3.47E 01	5.39E 01	3.02E 01
1.39E 01	3.37E 01	4.98E 01	2.92E 01
1.55E 01	3.36E 01	5.28E 01	2.75E 01
1.93E 01	3.39E 01	4.62E 01	3.19E 01
1.93E 01	3.35E 01	4.15E 01	3.39E 01
2.15E 01	3.37E 01	4.05E 01	3.34E 01
2.49E 01	3.46E 01	4.18E 01	3.42E 01
2.51E 01	3.29E 01	4.02E 01	3.19E 01
2.59E 01	3.55E 01	3.67E 01	3.07E 01
2.70E 01	3.35E 01	3.53E 01	3.15E 01
3.02E 01	3.34E 01	3.56E 01	3.42E 01

FILTER 5
67.6 SOURCE ZENITH ANGLE
726 M ALTITUDE (AGL)

AZIMUTH

.8	90.8	180.8	270.8
2.07E 01	1.71E 01	1.66E 01	1.62E 01
2.04E 01	1.71E 01	1.79E 01	1.57E 01
2.55E 01	1.74E 01	1.55E 01	2.52E 01
2.78E 01	1.82E 01	1.50E 01	1.88E 01
3.35E 01	1.79E 01	1.55E 01	2.00E 01
2.06E 01	1.29E 01	1.47E 01	2.08E 01
2.64E 01	1.62E 01	1.56E 01	1.85E 01
3.47E 01	2.08E 01	1.92E 01	2.11E 01
4.51E 01	2.32E 01	2.06E 01	2.49E 01
4.58E 01	2.67E 01	2.60E 01	3.15E 01
7.03E 01	2.88E 01	3.18E 01	3.35E 01
1.15E 02	3.57E 01	4.75E 01	3.97E 01
3.25E 02	3.42E 01	5.08E 01	3.87E 01
4.44E 22	3.55E 01	6.03E 01	9.01E 01
8.08E 02	4.22E 01	7.83E 01	5.91E 01
2.50E 02	5.39E 01	7.40E 01	5.15E 01
3.05E 02	1.14E 02	1.91E 02	1.42E 02
3.18E 02	1.43E 02	2.17E 02	1.45E 02

AZIMUTH

2.3	92.3	182.3	272.3
7.52E 01	5.04E 01	5.46E 01	3.91E 01
5.85E 01	3.27E 01	4.49E 01	2.49E 01
2.62E 01	2.76E 01	4.58E 01	2.53E 01
2.49E 01	2.04E 01	4.71E 01	2.49E 01
2.36E 01	1.99E 01	4.44E 01	2.41E 01
2.43E 01	1.93E 01	3.74E 01	2.39E 01
2.40E 01	1.90E 01	3.51E 01	2.22E 01
2.34E 01	1.78E 01	3.39E 01	2.31E 01
2.00E 01	1.90E 01	2.76E 01	2.48E 01
2.25E 01	1.92E 01	2.48E 01	2.16E 01
1.97E 01	1.47E 01	2.54E 01	1.86E 01
1.51E 01	1.36E 01	2.38E 01	1.74E 01
1.33E 01	1.32E 01	0	1.95E 01
1.61E 01	1.47E 01	1.68E 01	1.51E 01
1.57E 01	1.59E 01	1.88E 01	1.31E 01
1.54E 01	1.62E 01	1.64E 01	1.73E 01
1.41E 01	1.28E 01	1.34E 01	1.62E 01
1.19E 01	1.14E 01	1.20E 01	1.25E 01

GROUND LEVEL ALTITUDE
20 M

FLIGHT C-289

SKY AND TERRAIN RADIANCES (W/SR SQ M UM)

FILTER 4
38.9 SOURCE ZENITH ANGLE
1192 M ALTITUDE (AGL)

AZIMUTH

0	90.0	180.0	270.0
5.15E 02	1.41E 02	1.05E 02	4.00E 01
1.18E 02	1.73E 02	3.06E 01	1.26E 02
3.31E 02	7.04E 01	7.29E 01	2.07E 02
1.29E 02	1.15E 02	2.92E 01	3.39E 01
1.31E 02	2.22E 02	2.54E 01	4.35E 01
1.16E 02	4.21E 01	2.45E 01	3.36E 01
3.60E 02	3.65E 01	2.38E 01	3.12E 01
9.51E 02	4.08E 01	1.28E 02	3.05E 01
1.20E 02	1.29E 02	2.53E 01	7.51E 01
1.11E 03	3.80E 01	3.22E 01	1.71E 02
1.72E 02	1.25E 02	2.77E 01	1.65E 02
3.87E 02	2.12E 02	3.02E 01	4.92E 01
1.09E 02	4.80E 01	4.36E 01	2.48E 02
1.50E 02	5.70E 01	9.07E 01	1.00E 02
2.53E 02	6.61E 01	7.69E 01	5.86E 01
4.18E 02	1.76E 02	1.67E 02	1.32E 02
2.37E 02	1.84E 02	2.12E 02	1.33E 02
2.74E 02	1.23E 02	1.12E 02	1.49E 02

AZIMUTH

0	90.0	180.0	270.0
1.74E 02	6.89E 01	8.07E 01	8.56E 01
8.47E 01	4.23E 01	5.55E 01	5.33E 01
5.81E 01	3.33E 01	4.94E 01	4.22E 01
4.19E 01	2.20E 01	6.46E 01	3.06E 01
2.77E 01	2.87E 01	6.16E 01	2.41E 01
2.26E 01	2.95E 01	4.28E 01	2.79E 01
2.04E 01	2.94E 01	3.68E 01	2.79E 01
1.07E 01	2.76E 01	3.16E 01	2.56E 01
3.09E 01	4.70E 01	3.70E 01	2.30E 01
3.65E 01	2.23E 01	1.58E 01	2.07E 01
3.08E 01	2.43E 01	4.81E 01	1.78E 01
2.06E 01	2.26E 01	5.11E 01	2.95E 01
1.03E 01	3.56E 01	5.01E 01	3.26E 01
1.04E 01	1.48E 01	3.37E 01	1.23E 01
2.34E 01	3.06E 01	1.54E 01	1.43E 01
2.43E 01	1.02E 01	1.97E 01	3.18E 01
3.46E 01	2.90E 01	3.45E 01	2.91E 01
2.50E 01	3.62E 01	4.12E 01	3.04E 01

FILTER 4
40.4 SOURCE ZENITH ANGLE
258 M ALTITUDE (AGL)

AZIMUTH

0	90.0	180.0	270.0
4.55E 01	3.82E 01	3.52E 01	3.66E 01
5.95E 01	4.34E 01	3.82E 01	1.22E 02
6.86E 01	4.35E 01	3.50E 01	4.44E 01
7.84E 01	4.57E 01	3.04E 01	3.96E 01
1.08E 02	-0	2.73E 01	3.80E 01
1.63E 02	4.43E 01	2.62E 01	3.99E 01
3.47E 02	4.41E 01	2.64E 01	4.18E 01
1.39E 03	1.15E 02	1.10E 02	1.99E 02
2.02E 05	4.11E 01	7.59E 01	3.85E 01
1.63E 03	4.04E 01	1.62E 02	3.96E 01
5.75E 02	4.81E 01	3.08E 01	4.22E 01
4.53E 02	5.34E 01	3.31E 01	4.72E 01
3.03E 02	1.12E 02	3.91E 01	5.28E 01
5.17E 02	7.24E 01	5.25E 01	7.65E 01
3.08E 02	8.27E 01	5.79E 01	1.34E 02
2.28E 02	1.09E 02	6.23E 01	1.19E 02
3.26E 02	1.27E 02	9.03E 01	1.07E 02
1.71E 02	1.32E 02	1.00E 02	1.14E 02

AZIMUTH

0	90.0	180.0	270.0
1.12E 02	5.73E 01	5.07E 01	5.45E 01
5.06E 01	2.12E 01	3.67E 01	3.18E 01
1.53E 01	2.99E 01	3.43E 01	1.47E 01
1.81E 01	2.89E 01	3.42E 01	1.20E 01
2.11E 01	2.53E 01	5.43E 01	1.13E 01
1.20E 01	3.87E 01	2.98E 01	1.40E 01
1.63E 01	2.14E 01	4.06E 01	2.66E 01
3.40E 01	3.90E 01	3.86E 01	3.67E 01
2.93E 01	1.99E 01	4.36E 01	2.54E 01
2.73E 01	2.25E 01	4.06E 01	2.76E 01
2.89E 01	2.02E 01	4.77E 01	2.71E 01
1.94E 01	2.61E 01	4.34E 01	2.16E 01
2.38E 01	5.00E 01	3.64E 01	2.60E 01
2.24E 01	2.39E 01	3.53E 01	3.09E 01
2.68E 01	4.09E 01	3.21E 01	2.62E 01
2.21E 01	2.20E 01	2.23E 01	2.88E 01
1.33E 01	2.13E 01	2.02E 01	1.42E 01
2.61E 01	1.91E 01	3.43E 01	5.05E 01

FLIGHT C-354

GROUND LEVEL ALTITUDE
158 M

SKY AND TERRAIN RADIANCES (W/SR SQ M UM)

FILTER 4A
37.1 SOURCE ZENITH ANGLE
1116 M ALTITUDE (AGL)

ZENITH ANGLE	AZIMUTH 0	90.0	180.0	270.0
2.5	2.02E 02	2.06E 02	2.05E 02	2.05E 02
7.5	1.93E 02	2.20E 02	2.10E 02	2.03E 02
12.5	1.51E 02	-0	2.04E 02	1.83E 02
17.5	1.36E 02	1.45E 02	1.76E 02	1.61E 02
22.5	1.43E 02	1.96E 02	1.68E 02	1.48E 02
27.5	1.78E 02	1.85E 02	1.63E 02	1.33E 02
32.5	1.94E 02	1.87E 02	1.78E 02	1.31E 02
37.5	2.48E 02	2.08E 02	1.62E 02	1.53E 02
42.5	2.25E 02	1.53E 02	1.58E 02	1.52E 02
47.5	2.05E 02	1.72E 02	1.65E 02	1.55E 02
52.5	2.95E 02	1.99E 02	1.80E 02	1.58E 02
57.5	2.19E 02	2.23E 02	1.60E 02	1.66E 02
62.5	1.60E 02	2.74E 02	1.80E 02	1.57E 02
67.5	1.80E 02	2.32E 02	1.80E 02	1.37E 02
72.5	-0	2.47E 02	1.53E 02	1.39E 02
77.5	2.16E 02	2.27E 02	1.47E 02	1.27E 02
82.5	2.08E 02	1.84E 02	1.25E 02	1.26E 02
87.5	1.90E 02	1.15E 02	1.17E 02	1.23E 02

ZENITH ANGLE	AZIMUTH 0	90.0	180.0	270.0
92.5	1.79E 01	3.52E 01	3.46E 01	4.66E 01
97.5	1.58E 01	1.68E 01	2.13E 01	1.51E 01
102.5	1.09E 01	1.25E 01	1.41E 01	1.08E 01
107.5	8.99E 00	9.41E 00	1.14E 01	9.85E 00
112.5	8.36E 00	9.61E 00	1.32E 01	8.21E 00
117.5	1.52E 01	8.62E 00	8.17E 00	7.77E 00
122.5	7.64E 00	7.96E 00	1.29E 01	8.59E 00
127.5	6.24E 00	6.43E 00	1.21E 01	8.18E 00
132.5	7.36E 00	6.86E 00	7.31E 00	6.81E 00
137.5	6.59E 00	6.10E 00	5.61E 00	6.83E 00
142.5	7.09E 00	5.95E 00	6.81E 00	6.61E 00
147.5	7.21E 00	8.78E 00	1.01E 01	5.96E 00
152.5	6.95E 00	6.88E 00	7.73E 00	7.59E 00
157.5	5.92E 00	7.64E 00	5.94E 00	5.55E 00
162.5	9.40E 00	4.97E 00	5.53E 00	5.31E 00
167.5	5.02E 00	6.35E 00	4.92E 00	5.58E 00
172.5	6.41E 00	5.14E 00	5.66E 00	7.96E 00
177.5	1.03E 01	5.46E 00	7.75E 00	7.44E 00

FILTER 4A
39.4 SOURCE ZENITH ANGLE
549 M ALTITUDE (AGL)

ZENITH ANGLE	AZIMUTH 0	90.0	180.0	270.0
2.5	2.69E 02	2.83E 02	2.85E 02	2.77E 02
7.5	2.44E 02	2.12E 02	2.69E 02	2.68E 02
12.5	2.93E 02	2.48E 02	1.99E 02	2.36E 02
17.5	3.19E 02	2.06E 02	1.99E 02	2.26E 02
22.5	2.97E 02	2.32E 02	2.02E 02	2.33E 02
27.5	2.47E 02	2.01E 02	1.98E 02	2.21E 02
32.5	2.34E 02	1.95E 02	2.23E 02	2.36E 02
37.5	2.35E 02	1.97E 02	2.30E 02	2.37E 02
42.5	3.18E 02	1.65E 02	2.15E 02	2.32E 02
47.5	4.46E 02	2.51E 02	1.91E 02	2.37E 02
52.5	5.46E 02	2.69E 02	1.87E 02	2.29E 02
57.5	4.00E 02	1.80E 02	1.76E 02	2.27E 02
62.5	3.13E 02	1.44E 02	1.64E 02	2.07E 02
67.5	3.12E 02	2.06E 02	1.43E 02	2.00E 02
72.5	2.71E 02	2.23E 02	1.37E 02	1.72E 02
77.5	2.62E 02	1.85E 02	1.22E 02	1.56E 02
82.5	3.09E 02	1.80E 02	1.20E 02	1.31E 02
87.5	2.51E 02	1.35E 02	7.11E 01	1.21E 02

ZENITH ANGLE	AZIMUTH 0	90.0	180.0	270.0
92.5	1.70E 01	2.31E 01	1.67E 01	1.49E 01
97.5	1.85E 01	1.20E 01	1.26E 01	1.04E 01
102.5	7.49E 00	1.05E 01	1.76E 01	8.45E 00
107.5	7.99E 00	8.84E 00	8.98E 00	7.33E 00
112.5	7.58E 00	6.62E 00	8.11E 00	7.03E 00
117.5	6.82E 00	7.39E 00	8.88E 00	1.25E 01
122.5	8.05E 00	6.50E 00	7.51E 00	7.13E 00
127.5	9.07E 00	7.53E 00	1.25E 01	6.50E 00
132.5	7.10E 00	7.93E 00	9.31E 00	6.74E 00
137.5	4.72E 00	9.04E 00	9.58E 00	4.98E 00
142.5	5.39E 00	6.20E 00	5.55E 00	6.13E 00
147.5	6.33E 00	7.26E 00	6.78E 00	5.48E 00
152.5	8.22E 00	5.54E 00	7.11E 00	6.27E 00
157.5	5.48E 00	5.54E 00	7.75E 00	7.48E 00
162.5	1.67E 01	1.22E 01	1.32E 01	1.68E 01
167.5	5.74E 00	7.91E 00	6.29E 00	5.88E 00
172.5	8.31E 00	5.50E 00	6.77E 00	5.76E 00
177.5	1.55E 01	7.53E 00	1.19E 01	1.21E 01

FLIGHT C-360B

GROUND LEVEL ALTITUDE
158 M

SKY AND TERRAIN RADIANCES (W/SR SQ M UM)

FILTER 4B
37.0 SOURCE ZENITH ANGLE
1143 M ALTITUDE (AGL)

AZIMUTH 0	90.0	180.0	270.0
4.42E 01	-0	3.91E 01	4.15E 01
5.57E 01	-0	3.66E 01	4.24E 01
5.96E 01	4.31E 01	3.26E 01	4.16E 01
7.71E 01	4.00E 01	2.97E 01	4.30E 01
1.17E 02	4.09E 01	2.76E 01	4.17E 01
5.69E 02	4.07E 01	2.67E 01	4.06E 01
7.92E 03	4.04E 01	2.66E 01	4.17E 01
3.20E 05	4.21E 01	2.64E 01	4.12E 01
8.29E 02	4.04E 01	2.57E 01	4.07E 01
2.91E 02	3.75E 01	2.68E 01	3.84E 01
1.26E 02	4.07E 01	2.80E 01	3.98E 01
1.17E 02	4.22E 01	3.18E 01	4.20E 01
1.15E 02	-0	3.64E 01	4.39E 01
1.18E 02	4.70E 01	4.42E 01	5.10E 01
-0	5.57E 01	5.51E 01	5.89E 01
1.45E 02	7.25E 01	6.73E 01	6.84E 01
1.97E 02	9.32E 01	1.07E 02	1.03E 02
2.05E 02	1.23E 02	1.46E 02	1.32E 02

AZIMUTH 0	90.0	180.0	270.0
8.35E 01	8.20E 01	7.02E 01	7.21E 01
5.10E 01	4.97E 01	4.97E 01	3.52E 01
3.10E 01	3.77E 01	3.97E 01	2.57E 01
2.92E 01	2.25E 01	3.47E 01	2.12E 01
2.18E 01	1.90E 01	2.77E 01	2.05E 01
2.14E 01	1.70E 01	2.75E 01	2.09E 01
2.20E 01	1.32E 01	4.04E 01	1.64E 01
1.23E 01	2.34E 01	4.33E 01	1.55E 01
1.41E 01	1.46E 01	3.49E 01	2.38E 01
1.76E 01	3.22E 01	3.47E 01	2.38E 01
4.09E 01	2.34E 01	4.57E 01	2.12E 01
1.65E 01	2.30E 01	4.18E 01	2.88E 01
2.27E 01	3.00E 01	4.75E 01	3.24E 01
1.47E 01	3.34E 01	3.24E 01	3.35E 01
3.05E 01	2.03E 01	2.46E 01	2.71E 01
1.94E 01	2.78E 01	2.33E 01	3.52E 01
2.49E 01	2.94E 01	3.22E 01	2.53E 01
3.40E 01	2.79E 01	3.45E 01	3.43E 01

FILTER 4B
35.4 SOURCE ZENITH ANGLE
500 M ALTITUDE (AGL)

AZIMUTH 0	90.0	180.0	270.0
5.50E 01	5.29E 01	4.69E 01	4.98E 01
6.20E 01	-0	4.35E 01	4.96E 01
7.40E 01	-0	3.86E 01	4.72E 01
8.82E 01	5.13E 01	3.67E 01	4.73E 01
1.08E 02	4.97E 01	3.45E 01	4.41E 01
1.36E 02	-0	3.17E 01	4.21E 01
6.63E 02	4.92E 01	3.14E 01	4.38E 01
3.95E 02	5.07E 01	2.98E 01	4.07E 01
2.37E 02	4.97E 01	2.86E 01	3.94E 01
1.38E 02	4.97E 01	3.05E 01	3.85E 01
1.23E 02	5.07E 01	3.16E 01	4.09E 01
1.20E 02	5.24E 01	3.46E 01	4.36E 01
1.17E 02	5.83E 01	3.97E 01	4.57E 01
1.20E 02	-0	4.64E 01	4.87E 01
-0	6.64E 01	5.67E 01	6.29E 01
2.38E 02	7.58E 01	7.84E 01	7.64E 01
1.76E 02	9.63E 01	9.70E 01	1.04E 02
1.92E 02	-0	8.30E 01	1.07E 02

AZIMUTH 0	90.0	180.0	270.0
8.16E 01	9.99E 01	2.96E 01	4.97E 01
3.55E 01	3.95E 01	2.68E 01	2.10E 01
2.51E 01	2.17E 01	2.68E 01	1.99E 01
2.16E 01	1.74E 01	2.65E 01	1.54E 01
1.64E 01	1.69E 01	2.42E 01	1.19E 01
1.54E 01	1.31E 01	2.84E 01	1.21E 01
1.05E 01	1.26E 01	3.10E 01	2.30E 01
1.30E 01	1.23E 01	4.36E 01	1.74E 01
2.15E 01	1.75E 01	2.81E 01	2.21E 01
1.29E 01	1.85E 01	4.07E 01	1.96E 01
8.57E 00	2.00E 01	3.14E 01	4.78E 01
2.61E 01	2.95E 01	5.17E 01	2.74E 01
2.49E 01	2.65E 01	4.65E 01	3.05E 01
2.83E 01	2.93E 01	2.86E 01	3.13E 01
2.97E 01	2.35E 01	3.95E 01	3.53E 01
3.08E 01	3.44E 01	3.59E 01	3.17E 01
2.80E 01	3.38E 01	3.60E 01	3.25E 01
1.10E 01	3.18E 01	1.43E 01	1.38E 01

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APPENDIX B

ACRYLIC - FIRE SAFETY ASPECTS

APPENDIX B

Plexiglas acrylic sheet in architecture 8.26/Roh

Plexiglas® and Fire

Plexiglas must be used with an appreciation for the fact that it is a combustible material.

In general the same fire precautions that are observed in connection with the handling and use of any ordinary combustible material should be observed when handling, storing or using Plexiglas.

Building codes and Underwriters' Laboratories standards define good practice in the use of Plexiglas for light transmission and control on a design and engineering basis that takes into account the combustibility and fire characteristics of the material.

The fire hazard of uses of Plexiglas can be kept at an acceptable level by complying with building codes and applicable Underwriters' Laboratories standards, and observing established principles of fire safety. We list below the fire response characteristics of Plexiglas in one column and the design, engineering, and fire protection implications of the characteristics in an adjacent column.

Fire Response Characteristic	Recommended Practice
The ignition temperature of Plexiglas is higher than that of most woods but it will ignite readily; and when involved in fire, will burn vigorously and generate heat rapidly.	Install Plexiglas away from sources of intense heat or flame. Enclose edges of Plexiglas components. Observe building code stipulations and restrictions. Do not use more Plexiglas than required to perform the function required of it. Employ fire protection systems, e.g., sprinklers, fire detectors, automatic vents as hazard analysis indicators.
Plexiglas softens when heated above 260°F which is approximately 300° below its ignition temperature.	Do not use Plexiglas as a supporting element or in any location where resistance to fire penetration is required.
Plexiglas if held in position when burning, will drip burning droplets.	In overhead lighting, mount Plexiglas in free channel mountings to assure fallout prior to ignition. Extinguish burning Plexiglas with water or fire extinguishers.
When installed as a wall or ceiling finish or when laminated to a substrate, Plexiglas provides a surface over which flame may spread rapidly and release heat and gases contributing to flashover.	Do not install Plexiglas as applied wall or ceiling finish or as a substrate surfacing material for large interior surface areas in building applications unless the areas are protected by an automatic sprinkler system.
Large area installations of Plexiglas such as transparent enclosures are not provided for in building code regulations because they do not conform to area limitations and therefore require special permits based on analysis of all relevant fire-safety considerations.	Relevant considerations are use of the structure (occupancy); location (exposure); height and area; nature of interior arrangements (decorations, finishes and furnishings); availability and construction of fire exits; need for special fire protection systems such as sprinklers, automatic heat and smoke vents, early warning devices and deluge systems or water curtains.
Burning plexiglas does not produce either excessive quantities of smoke or gases more toxic than those produced by burning wood or paper. The concentration of carbon monoxide and/or carbon dioxide released by burning Plexiglas is a factor of the quantity of Plexiglas involved and the conditions of burning.	The use of Plexiglas is not restricted because of the character of its products of decomposition but because of its combustibility and burning characteristics.

Copies of the approvals of Plexiglas under various codes will be made available on request. In addition, reports on the status of Plexiglas under Federal Government regulations will be provided promptly. Assistance will also be provided by *Rohm and Haas code consultants* and engineers in obtaining approvals for installation of Plexiglas which constitutes justifiable exceptions to existing restrictions. A considerable amount of information is available to suport such applications. Approvals of general interest include: ICBO Research Recommendation No. 1084; BOCA Report No. 72-33 and SBCC Report No. 7246; New York City Board **of Standards and Appeals Calendars 444-60-SM, 657-63-SM; New York City Department of Water Supply, Gas & Electricity approval for use in signs and lighting fixtures; New York City MEA 107-69-M; California Fire Marshal File No. A2560-007.**

APPENDIX C

FEDERAL AVIATION ADMINISTRATION LETTER

COMMERCIAL FOG EQUIPMENT

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

AERONAUTICAL CENTER
P.O. BOX 25082
OKLAHOMA CITY, OKLAHOMA 73125

DATE:

IN REPLY REFER TO:

SUBJECT: Smoke producing machine.

April 28, 1978

TO: Mr. LaCarrubba, Grumman Aerospace

I am taking this means to send you information on the Pepper Fog smoke machine we use here to provide visual obscuration in test cabin conditions. The General Ordinance Equipment Company has a distributor in Hempstead, N. Y. by the name of The Charles Greenblatt Company, telephone (516) 538-3650.

The Pepper Fog machine is used for law enforcement to dispense tear gas during riot control. The light molecular oil used as the vehicle for dispensing the tear gas is what we use as the inert screening smoke. Sun Oil Co. Sunthene 410 is the type oil used which is burned through the pulse jet engine built in the machine. The resulting residue is a light gray fog very obscuring and yet non hazardous to humans. We have many hours working in the fog without respiratory or eye protection. Even though there is a fine residue, there are no deposits or film that one can detect after about an hour or so. Self contained batteries start the machine which burns regular gasoline as the fuel to burn the oil.

If the Greenblatt Company can not provide you with more details on the system, please contact me again and I will get more information. Cost for our machine in 1971 was $380.00; the oil per quart - $6.80 and prices may vary as you could expect.. The machine is portable - about 28 pounds.

J. D. GARNER -AAC-119
EVACUATION RESEARCH
Civil Aeromedical Institute
Oklahoma City, Ok.
(405) 686-4853

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